

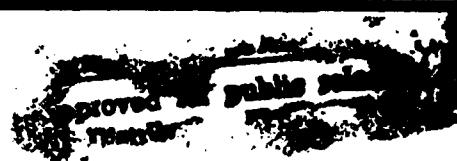
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AN ANALYSIS OF
STOPPING CRITERIA IN
ARTIFICIAL NEURAL NETWORKS

THESIS
Bruce Kostal
Captain, USAF

AFIT/GST/ENS/94M-07



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**AN ANALYSIS OF STOPPING CRITERIA
IN ARTIFICIAL NEURAL NETWORKS**

THESIS

**Presented to the Faculty of the Graduate School of Engineering
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Operations Research**

**Bruce Kostal, B.S., M.B.A.
Captain, USAF**

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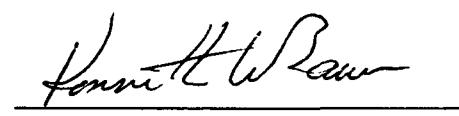
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Preface

This study examines artificial neural networks. In particular, I attempted to find a better artificial neural network (ANN) by determining the optimal point at which to terminate training. The idea for the study was recommended to me by my advisor, Lt Col Ken Bauer, and two of his doctoral students, Capt Jean Steppe and Capt Lisa Belue. The results of this study provide useful information regarding determining when to stop ANN training and deciding upon a final set of ANN weights. I would like to thank several people for their contributions to this thesis effort. Lt Col Bauer has spent many hours guiding and inspiring me after my original idea for a topic fell through. Lt Col Jim Shedd served as a reader for my thesis and provided an independent viewpoint and insight into my written effort. Capt Steppe, Capt Belue, and Capt Greg Reinhart have provided valuable knowledge on artificial neural networks, going beyond the information found in the literature.

Perhaps the greatest thanks goes to my family. First of all, the greatest thanks goes to my wife Donna who managed my life for the past eighteen months. Next, to my daughter Kara who tolerated my absences and dutifully told me to go study when she did not want me around. And finally to Whitney who, by coming into this world on 20 February 1994, provided me the incentive to work hard to finish this thesis so I would be in a position to witness her arrival.

Bruce Kostal

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Abstract

The goal of this study was to decide when to terminate training of an artificial neural network (ANN). In pursuit of this goal, several characteristics of the ANN were monitored throughout ANN training: classification error rate (of the training set, testing set, or a weighted average of the two); moving average classification error rate; measurements of the difference between ANN output and desired output (error sum of squares, total absolute error, or largest absolute error); or ANN weight changes (absolute weight change, squared weight change, or relative weight change). Throughout this research, the learning rate was held constant at 0.35. The momentum was not used because the primary interest of this study was evaluating when to terminate training as opposed to the speed of reaching a decision. The ANN structure was held constant with two input features, two output classes, and one hidden layer. Finally, the practice of training after processing each exemplar was followed. Results indicated three conclusions. First, multiple runs are required for ANN analysis because ANNs are not guaranteed to converge to the same solution. Second, the classification error rate, a moving average of the classification error rate, and the total absolute error (all computed on the testing set) provided a similar final classification. Third, once the stopping criteria functions cease to decrease, select a set of ANN final weights at random. On average, they yielded as low as or lower classification error rate and variance of the classification error rate than other possible choices.

AN ANALYSIS OF STOPPING CRITERIA IN ARTIFICIAL NEURAL NETWORKS

I. Introduction

1.1 Background

The idea of a computer or machine controlling our lives has been around for a long time. Until recently, machines could only do what they were told (which, due to some programming errors, may not have been what we wanted them to do). Now, however, through artificial intelligence and artificial neural networks, we are attempting to perform much more complicated tasks with computers. This paper will explore a method to improve an artificial neural network, or ANN. In particular, the study attempts to find a better way to determine the appropriate time to terminate ANN training.

Artificial neural networks are a relatively new area of research. In general terms, an ANN is a mathematical function which 'learns', thereby mimicking the work of the human brain. By analyzing training data, where the output is known, the ANN assigns weights to functions to 'learn' from its past experience. Following this iterative scheme, the network learns from training data, continually improving in its ability to predict the answer to a 'yes-no' question. Next, the ANN moves to a separate set of testing data to determine if the weights are correct. The goal of this continued improvement is the ability to predict a result based upon independent input factors.

Artificial intelligence and artificial neural networks are different. Guyon describes this difference as follows: "The main differences between the classical approach of Artificial Intelligence (AI) and Neuron Networks (NN) is that AI requires

considerable detailed programming whereas NN rely heavily on learning" (Guyon, 1991: 243).

1.2 Problem Statement

An ANN currently has the capability to improve in its ability to predict an output based upon inputs. However, it is extremely difficult to determine when this improvement ceases to occur and an overlearning of the training data begins. This study measured the classification error rate of a separate validation set to search for a criterion which best predicted the point at which to terminate ANN training.

1.3 Scope

The goal of this study was to perform artificial neural network (ANN) analysis. The ANN algorithm used was the back propagation algorithm. The study used classification error rate of the validation set as a measurement standard to evaluate several proposed stopping criteria. Each proposed stopping criterion had a resulting output function which changed during ANN training. The study compared these stopping criteria functions with the classification error rate of an independent validation set which was assumed to be the best representation of the true population. The stopping criterion which had the lowest error classification rate was judged to be best. Then, this best stopping criterion was compared to more commonly used stopping criteria measures involving the classification error rate. The goal was to find a more automated and less arbitrary method of selecting the optimum or near optimum point at which to terminate ANN training.

As part of the research, decisions were made regarding methods and variables within the ANN. As Nelson notes, the tasking of an artificial neural net programmer is different from that of a normal computer programmer. The ANN programmer's task is to "specify transfer functions (equations to determine thresholds), training laws (rules that set initial weights and equations that modify weights), and the struc-

ture of the network (number of nodes, layers, and interconnections)”. Additionally, the programmer must decide “if and how often the processing elements would update (continuously or periodically)” (Nelson, 1991: 55). Within this context, the study involved programming to search for an optimal stopping criterion or criteria.

1.4 Overview

This paper begins with a review of the literature found in Chapter 2, in which ANNs and eleven potential stopping criteria are discussed. The study continues with an explanation of the methodology which was used (Chapter 3). Additionally, Chapter 3 details the Exclusive OR (XOR) problem and the meshed data set problem which were used for this study. Chapter 4 gives the results of ANN experiments on the XOR and the meshed data set problems. Finally, Chapter 5 outlines the general procedure developed and refined in this study and lists areas of future research.

II. Literature Review

This chapter provides a literature review of artificial neural networks (ANN), with particular emphasis on the area of this study. Specifically, it will cover general information, building blocks of the back propagation algorithm, the back propagation algorithm itself, and close by covering the area of this study, criteria for determining when to stop training the artificial neural network.

2.1 General Information

To begin, the reader needs a general picture of the artificial neural network. An ANN is a family of algorithms used in learning which are based upon concepts developed from observing how the human brain works (Müller, 1990: 12). They use parallel processing to look at the entire picture instead of the processing each input individually. Nelson provides an example of this parallel processing which is reproduced in Figure 1. If each input is individually processed as in the traditional

D_N'T THR_W _W_Y
TH_ _LD B_CK_T
_NT_L Y_ KN_W
WH_TH_R TH_ N_W
N H_LDS W_T_R.

S P_NNY S_V_D
S P_NNY
_RN_D

_ST_TCH _N
T_M_ S_V_S
N_N_

Figure 1. Missing Letter Example

computer, that is, one letter or information bit at a time, the saying would be extremely difficult to read. For example, it would be virtually impossible to even know that the figure contained three separate sayings if the information were processed in this piecemeal manner. By stepping back and processing more than one input at a

time, however, the true picture becomes clear. The reader can see that the vowels are missing and quickly fill in the missing letters to come up with the three sayings (Nelson, 1991: 15 - 16). The ANN tries to do the same thing; it takes more than one input and puts those inputs together to learn and provide correct classifications.

Artificial neural networks go by many names, such as the following: neural networks, parallel distributed processing models, connectivist or connectionism models, adaptive systems, self-organizing systems, neurocomputing, or neuromorphic systems (Nelson, 1991: 19). Each name may mean something slightly different. This paper will use the term artificial neural network or ANN.

In his overview, Lippmann presents a taxonomy of six types of ANNs. Lippmann's diagram is reproduced in Figure 2. This taxonomy is divided based upon

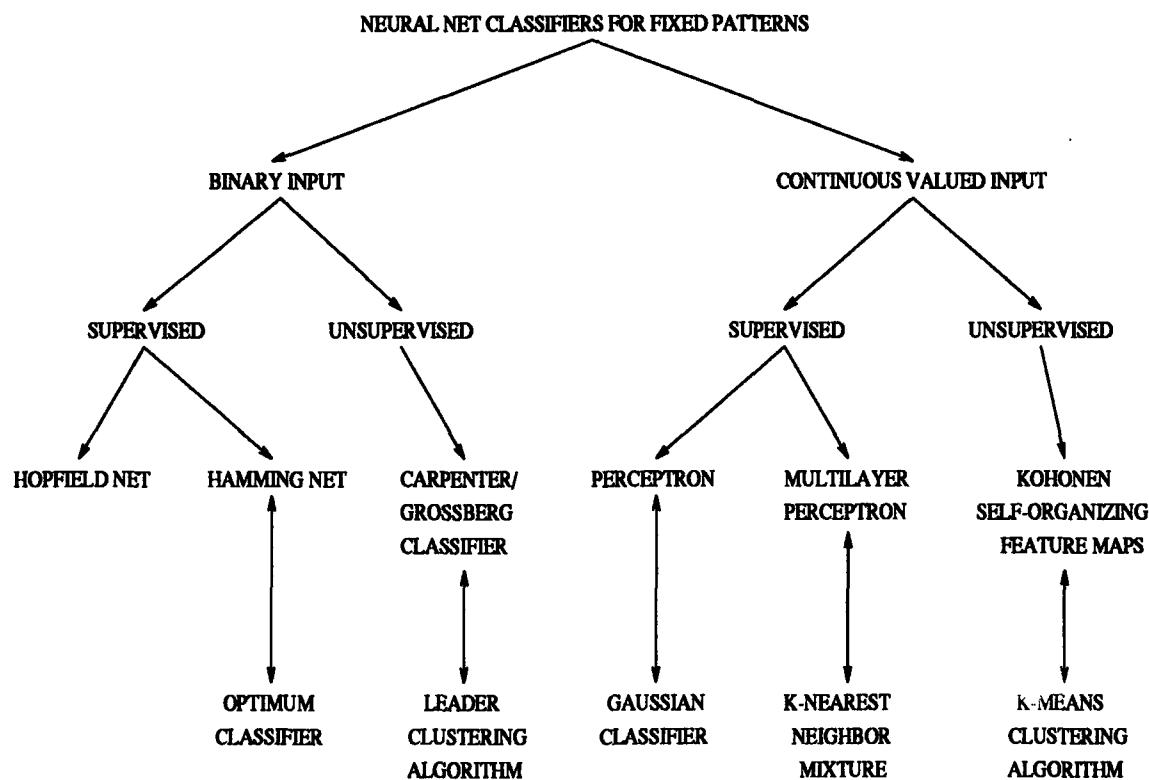


Figure 2. Types of Artificial Neural Networks

the method used by the neural network. The first division is based upon whether the input data is binary or continuous. The continuous algorithms can also be used with binary input data. The second dividing test is based upon whether or not the training is supervised. Finally, the supervised training is again split (Lippmann, 1987: 6-7). This research will use continuous input, supervised training, and multiple layers.

Before going further into neural networks, it is best to define the terms which follow:

- Epoch: A cycle of presenting all training cases one time (Weiss, 1991: 85).
- Exemplars: Example data points for which the output class is known. The network is trained using these data points (Tou, 1974).
- Multilayer perceptrons: “[Feedforward] nets with one or more layers of nodes between the input and output nodes.” The additional layers are where the hidden layers reside (Lippmann, 1991: 15).
- Feature: An input attribute of the output to be measured which contains useful information for distinguishing an item between the various classes. A feature is similar to an independent variable (Tou, 1974).
- Feedforward network: This type of network exists when no “processing element output can be an input for a node on the same layer or a preceding layer” (Nelson, 1991: 50-51). A feedforward network is the usual type of artificial neural network found in the literature.
- Hidden Units: Neurons which are neither input or output units. They are located between the input and output units in a multilayer neural network (Guyon, 1991: 224).
- Training Procedure: The way a neural network ‘learns’. This will be covered in greater detail later.

2.2 Artificial Neural Network Building Blocks

Before covering the specific steps to be taken in the back propagation algorithm, it is first necessary to understand some of the building blocks that the algorithm will use. These building blocks are covered in this section.

2.2.1 Single Layer Perceptron. The simplest form of artificial neural network is the single layer perceptron. It is characterized by weights and features (independent input variables) (Weiss, 1991: 84).

A single layer perceptron can be represented as the weighting scheme or evaluation criterion which allows one to draw a dividing line in a two-dimensional space which segregates two types of outputs into separate, distinct regions. For an example, see Figure 3 which is reproduced from Lippmann. In Figure 3, there are two

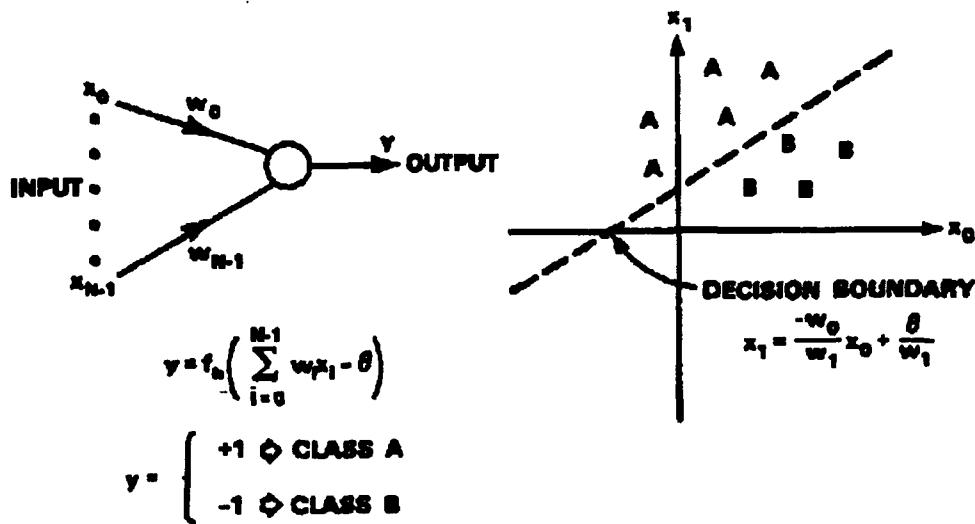


Figure 3. Single Layer Perceptron

classes of outputs (A and B). These outputs can be separated by the line in the figure. After this line is drawn, one need only know on which side of the line a point is to determine whether it is type A or type B. Using a learning scheme, a line can be drawn to separate A and B based upon the input features, which would be the

values of x_0 and x_1 here. In multidimensional space, a hyperplane divides the region (Lippmann, 1987: 13).

The previous example (Figure 3) is linearly separable, meaning a line can be drawn between the two classes. “When the two classes are linearly separable, the perceptron training procedure will be guaranteed to converge to an answer” (Weiss, 1991: 85). (The perceptron training procedure uses the back propagation algorithm which will be explained in Section 2-3.) However, if the classes are not linearly separable, “the procedure will not converge and will keep on cycling through the data forever” (Weiss, 1991: 87). Linear separability is the exception rather than the rule. Minsky and Papert illustrated this weakness of the perceptron. They pointed out that if the individual classes investigated under the single perceptron algorithm method can not be separated by a hyperplane, then the single perceptron algorithm is not appropriate (Lippmann, 1987: 15).

Training or adjustment of the weights occurs in the single layer perceptron only when an error (misclassification) occurs. “When a false positive error occurs, i.e., the true answer is 0 and the perceptron says 1, each weight is adjusted by subtracting the corresponding value in the input pattern, and 1 is subtracted from the threshold. For false negatives, each weight is adjusted by adding the corresponding value in the input pattern, and 1 is added to the threshold. The hope is that each adjustment will move the weights closer to the true weights” (Weiss, 1991: 85).

2.2.2 Multilayer Perceptron. Multilayer perceptrons are more flexible than the single layer perceptrons. Single layer perceptrons are only capable of dividing a space with one hyperplane. Multilayer perceptrons, on the other hand, can “form any, possibly unbounded, convex region in the space spanned by the inputs.” The convex regions formed in the multilayer perceptron can have at most the number of sides as there are nodes in the first layer of the network (Lippmann, 1987: 16).

Weiss deals with either one or two hidden layers in the multilayer network. With one hidden layer, he notes that the multilayer network can “implement most decision surfaces, and can closely approximate any decision surface (Weiss, 1991: 94). Regarding the three layer network which includes two hidden layers, Weiss lists its attributes as being able to “implement any separating decision surface when sufficient hidden units are represented in the two layers” (Weiss, 1991: 94). While Weiss compliments the more capable network with more than one hidden layer, he concludes that one hidden layer is sufficient and that “additional layers do not add any representational power to the discrimination” (Weiss, 1991: 94). This paper concentrates on the case where one hidden layer is used.

2.2.3 The Training Process. Applications of neural networks involve four levels of learning: No learning (fixed weights), supervised learning, semi-supervised learning, and unsupervised learning (Guyon, 1991: 233). Supervised learning involves minimizing some cost function E which accumulates the errors as measured by the difference between the actual outputs and the desired outputs (Guyon, 224). (The function E is an error function tracking the difference between the ANN output and the desired output. The actual form of E varies. It may be represented by the absolute value of the error, the squared error, or some other form. Forms of the function E to be investigated will be explained later. For the mathematical formulation of the various functions E , please see Appendix B.) The goal is to minimize this function E . Guyon lists two techniques for this minimization: Monte Carlo techniques and gradient descent. Guyon prefers gradient descent because, although it usually leads to a suboptimal solution (or a local maximum or minimum), it is computationally less intensive than the Monte Carlo techniques (such as simulated annealing) (Guyon, 1991: 224). Supervised learning and gradient descent techniques were used in this study. Additionally, procedures exist to compensate for the gradient descent’s propensity to find suboptimal solutions. These procedures will be covered later.

Generally, there are three versions of algorithms used to train a neural network: Hebb's rule, the perceptron algorithm, and the Widrow-Hoff algorithm. These latter two algorithms are basically the same; the difference being that, under the perceptron, training is only done if the network gives the wrong answer. Under the Widrow-Hoff algorithm, training is done as long as the answer is not perfect (Guyon, 1991: 220 - 221). This study exclusively used the Widrow-Hoff algorithm. The mathematical rules for this algorithm will be covered later in the back propagation section.

To conduct the training process, the data is split into two groups. The first group is called the training set. The training set is used "to design the classifier" (Weiss, 1991: 26). This means that the training data is given to the artificial neural network and weights are adjusted, rewarding correct responses and penalizing incorrect responses. The second group of data is called the testing set. The testing set is not given to the ANN until the training set has reached a classifying decision. After this decision is reached, the testing set is given to the ANN and an error rate (or some other measure such as error sum of squares or total absolute error) is determined. This error rate of the artificial neural network on the testing set is known as the test sample error rate (Weiss, 1991: 28). Additionally, data can be divided a third time into a set called the validation set which can be used after training and testing are complete (Wiggins, 1991: 28).

Essentially, the learning or training rules specify an "initial set of weights and indicate how the weights should be adapted during use to improve performance" (Lippmann, 1987: 4). The key to this learning process is the adjustment of the weights. To begin with, the artificial neural network is given the training data. Weights which lead to the ANN correctly identifying the response are strengthened and weights which lead to incorrect responses are weakened. The key here is getting the response trained to fall on the correct side of the threshold level (Nelson, 1991: 48).

Weiss addresses the concept of sufficiency of data. He states a “widely used heuristic” that “a network should average at least ten samples per weight in the network” (Weiss, 1991: 104). Additionally, Weiss concludes that larger sample sizes (of 1000, 5000, or higher) yield very accurate results. On the other hand, he notes that the lack of data is more often the limiting factor. Given this potential dearth of data, Weiss recommends splitting the data in the following proportions: $\frac{2}{3}$ for the training set and $\frac{1}{3}$ for the testing set (Weiss, 1991: 28 - 30).

2.2.4 Error Rate. In the absence of linear separability, errors will occur in the artificial neural network learning process. Throughout the process, then, Weiss notes that the goal could also be stated as “finding the best fit to the sample data without overspecializing the learning system” (Weiss, 1991: 37).

When developing a learning system, the apparent error rate of the system developed from a sample (the classification error rate of the training set) is the ‘obvious’ place to begin. However, Weiss notes that the apparent error rate is “a poor estimator of future performance.” Weiss continues “In general, apparent error rates tend to be biased optimistically. The true error rate is almost invariably higher than the apparent error rate. This happens when the classifier has been overfitted (or overspecialized) to the particular characteristics of the sample data” (Weiss, 1991: 24). The best way to correct for this is to ensure a random sample of data has been obtained. This maximizes the opportunity for finding the true error rate. Regarding this quest, Weiss noted that “humans have difficulty doing things randomly” (Weiss, 1991: 26). Therefore, using a machine or computer to decide upon the random sample is recommended (Weiss, 1991: 26).

Weiss notes that resampling methods can provide an even better estimate of the true error rate, especially when the data set is small. A simple form of resampling technique is called the leaving-one-out technique. In it, the entire sample is treated as part of the training set except for one data point which is treated as

the testing set. Each data point is iteratively rotated into the status of the testing set. Because of the extensive number of iterations required under this technique (one iteration for each exemplar), Weiss recommends using it only on smaller sample sizes. With the continuing evolution and improvement of computer design and speed, however, the extensive number of iterations required is less of a problem than it once was. The leaving-one-out technique is also noteworthy because it is unbiased and accurate. However, it has a weakness of a relatively high variance, especially in smaller samples (Weiss, 1991: 30 - 33). As an alternative, Weiss mentions the bootstrapping technique (Weiss, 1991: 33 - 36).

Resampling methods such as the leaving-one-out technique or bootstrapping can be used for other statistical parameters besides estimating error rate. Weiss mentions that they can be used for evaluating how many variables to put in the model and evaluating how many nodes to put in the decision trees (Weiss, 1991: 37).

Since the particular resampling technique depends upon the sample size, Weiss offers guidance. Use cross-validation if the sample size is greater than 100. Use leaving-one-out if the sample size is less than 100. Weiss further states that, in the situation of 'very small samples' (which he defines as fewer than 50 cases), bootstrapping techniques "may be computed" (Weiss, 1991: 38).

Weiss points out that adding additional features, unlike in regression, may actually yield worse results. He lists two possible reasons. First, the predictive ability of some classifiers may decrease with poor or noisy data. Second, some methods may overweigh redundant features which essentially measure the same thing. The effect here is that of counting something twice. Since actual data is often noisy or redundant, the impact of adding weak features to the data set may be to degrade performance. To limit this impact, feature selection is used to minimize the effect of noise and redundancy. The effect of feature selection is to throw out or eliminate

features which do not have positive impact upon the predictive capability of the classification scheme (Weiss, 1991: 40).

The true error curve is a function of the complexity of the model. As complexity increases, the true error rate initially decreases before leveling off. After this flattening, it wanders around for a period before increasing. Using this fact, Weiss concludes that, if the error rates are close, one should select the simpler model. He expands this to explain the one-standard error heuristic, which “selects the simplest solution that falls within one standard error of the minimum error rate solution” (Weiss, 1991: 45 - 46).

2.2.5 *The Sigmoid Function.* The sigmoid function is another tool used in neural networks which must be understood before discussing the actual processing algorithm. It is used as a ‘limiter,’ or something that distinguishes between the images or desired responses. There are three types of limiters: hard limiters, threshold logic elements, and sigmoidal nonlinearities (Lippmann, 1987: 4). See Figure 4, reproduced from Lippmann.

Recently, the sigmoid unit, a modified version of the McCulloch-Pitts neuron, has increased in popularity. The sigmoid unit uses the smoother hyperbolic tangent function which has the advantage of being a differentiable function, making it possible to use gradient search techniques for training the multilayer neural network (Guyon, 1991: 223). Nelson stresses the advantage of the sigmoid function by saying that “both the function and its derivatives are continuous” (Nelson, 1991: 48).

Nelson lists two sigmoid transfer functions. In both cases below, y is the output of the sigmoid function and x , the input, is any real number. First, if the transfer function uses outputs of 0 and 1, the transfer sigmoid is defined as follows:

$$y = \frac{1}{1 + e^{-x}}$$

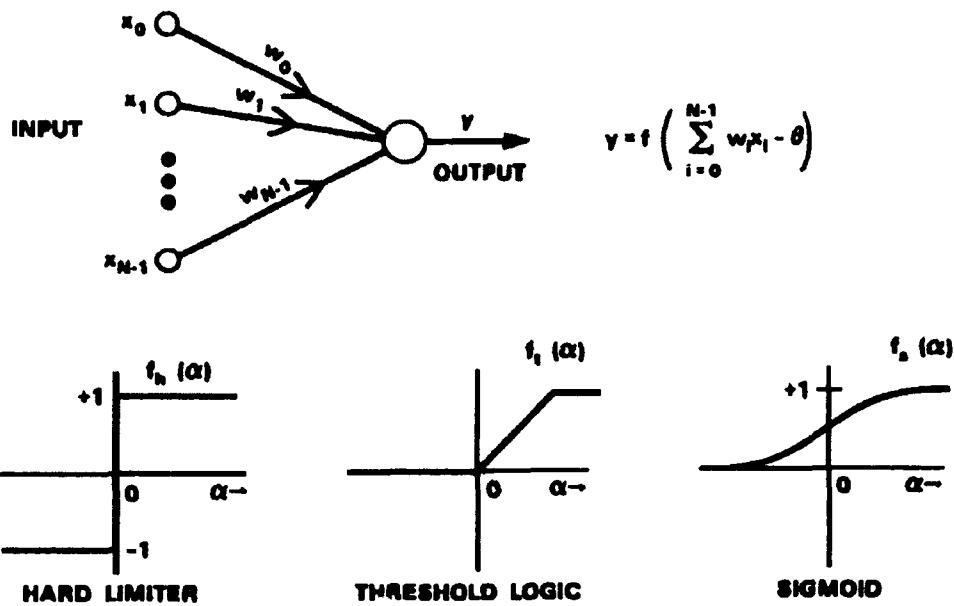


Figure 4. Types of Limiters

On the other hand, if the transfer function uses outputs of -1 and +1, the transfer sigmoid is defined as follows:

$$y = 1 - \frac{1}{1+x}$$

for $x \geq 0$ and

$$y = -1 + \frac{1}{1-x}$$

for $x \leq 0$ (Nelson, 1991: 47-48).

Regarding Nelson's two choices, Guyon states that a 0 is used instead of -1 in scaling for 'convenience' (Guyon, 1991: 220).

Regardless of the sigmoid function used, the objective is to allow the artificial neural network to emulate the brain. Within the brain, each nerve cell can respond to as many as 200,000 inputs, although 1,000 to 10,000 inputs are more typical. The inputs are either 'fire' or 'do not fire,' similar to a 0-1 variable (Nelson, 1991: 40).

These sigmoid functions provide the mathematical background for either firing or not firing.

2.2.6 Least Mean Square. The least mean square learning system (or LMS) is an alternative similar to the perceptron and serves as an introduction to the back propagation algorithm. In LMS, the output is now the real number which results from the equations as opposed to the adjusted integer used under the perceptron technique. Therefore, its output O is given as follows:

$$O = \sum_i w_i I_i + \theta$$

where w_i is the i th weight, I_i is the i th input, and θ is a constant or bias term. Notice that the LMS technique consists of one output and one layer.

Under the LMS procedure, the true output, denoted as T , is an integer. The actual output, O , is real. The goal of LMS is to minimize the average square of the difference between these two values (Weiss, 1991: 87 - 88).

The training procedure under the perceptron procedure and LMS is the same for the most part. A key difference, however, is the adjustments. Since both T and O are limited to integers under the perceptron procedure, there is a chance for an exact match which would result in no adjustment. Under the LMS, on the other hand, exact matches are rare because O is a real number. Therefore, adjustments are more frequent under LMS (Weiss, 1991: 89).

LMS offers another advantage. Since LMS seeks to minimize the difference in terms of the minimum error distance, it tends to perform well even if the classes are not linearly separable (Weiss, 1991: 89).

LMS seeks to converge to a solution using the technique known as gradient descent. Gradient descent techniques have two weaknesses. First, they may oscillate and not converge. Second, if they do converge, they are not guaranteed to converge to

the correct answer (Weiss, 1991: 89). To improve performance in spite of this picking of the local minima, Lippmann recommends the following alternatives: “allowing extra hidden units, lowering the gain term used to adapt weights, and making many training runs starting with different sets of random weights” (Lippmann, 1987: 18). To test for lack of convergence, Weiss recommends repeating the training sessions several times on the complete sample. If these different sessions, each starting from different initial weights selected at random, result in different final weights, a likely conclusion is that a local minima has been found. To correct for this local minima, Weiss recommends either decreasing the learning rate or increasing the momentum (Weiss, 1991: 106). The concept of learning rate and momentum arise in the back propagation algorithm, which will be covered next.

2.3 Back Propagation

The previous information (the multilayer perceptron, the training process, the sigmoid unit, and the least mean squares technique) come together in the back propagation algorithm. This back propagation algorithm is the key to this study of artificial neural networks.

Guyon praises the error back propagation algorithm as an “easy and elegant way of performing on-line (or *stochastic*) gradient descent to train neural networks” (Guyon, 1991: 226). The basic concept of this procedure is that outputs are first computed during the forward pass through a network of perceptrons. The output is next compared to the desired output. In the same manner, the discrepancy of the hidden unit outputs from the desired output level are computed during the back propagation pass and weights are adjusted accordingly. Finally, a least mean squares stopping criterion is used (Guyon, 1991: 227).

2.3.1 Back Propagation Algorithm. This section covers the actual back propagation algorithm. It is based primarily on the algorithms as presented by

Lippmann (Lippmann, 1987: 17) and Rogers (Rogers et al., 1990: 56). In general, it is a iterative sequence based upon minimizing the mean square error “between the actual output of a multilayer feed-forward perceptron and the desired output” (Lippmann, 1987: 17). For distinguishing between results, the back propagation algorithm uses the sigmoid function. The algorithm is a five step process.

Step One: Initialize the weights. Lippmann recommends initializing the weights to “small” random values (Lippmann, 1987: 17). Rogers states that the weights are normally from a uniform distribution between -.5 and .5 (Rogers et al., 1992: 56). Weiss recommends setting the initial weights randomly to numbers between 0 and 1 (Weiss, 1991: 85). The values chosen simply must not all be the same; if they are, the training will fail (Wiggins, 1991: 19).

Step Two: Feed data to the neural network to conduct the training process. The data contains the input values as well as the desired output. In a typical application such as pattern recognition, the desired pattern would be assigned an output of 1; all other outputs would be assigned a value of 0. Lippmann presents two alternatives for treating the training data set. First, all of the training data may be presented continuously. Second, the user may break up the training data into smaller sets, then use the different training data sets in a cyclical fashion. Repeat either of these two techniques until the weights stabilize. Lippmann does not recommend one technique over the other. This study will treat the training data as one complete set.

Step Three: Use the sigmoid nonlinearity to calculate the values of the outputs, a vector of y_s .

Step Four: Adjust the weights as appropriate. This is where the back propagation algorithm gets its name because the algorithm starts at the output nodes and works backwards. Weights are adjusted according to the following equation:

$$w_{ij}(t + 1) = w_{ij}(t) + \eta \delta_j x_i$$

where w_{ij} is the weight from node i (which may either be an input or a hidden node) to node j at time t ; x_i is either the output of node i or is an input; η is a gain term or learning rate; and δ_j is an error term for node j .

The actual computation of δ_j depends upon where j is located in the artificial neural network. First, if j is an output node, then

$$\delta_j = y_j(1 - y_j)(d_j - y_j)$$

where d_j is the desired output of node j and y_j is the actual output.

On the other hand, if j is an internal hidden node, then δ_j is determined as follows:

$$\delta_j = x_j(1 - x_j) \sum_k \delta_k w_{jk}$$

where k is over all nodes in the layers above node j .

Lippmann concludes step four by noting “convergence is sometimes faster if a momentum term is added and weight changes are smoothed by” the following equations:

$$w_{ij}(t + 1) = w_{ij}(t) + \eta \delta_j x_i + \alpha(w_{ij}(t) - w_{ij}(t - 1))$$

where $0 < \alpha < 1$.

Step Five: Return to step two and repeat until either the maximum number of iterations is reached or the error is within tolerance.

2.3.2 Comments on Lippmann's Back Propagation Algorithm. Others have provided relevant inputs to the back propagation algorithm. Some of those comments will be covered next.

As with any gradient search technique, an important factor is knowing when to quit. Weiss recommends two possible stopping criteria which may be used in such a way that a stop is initiated as soon as either of the criteria is met. In addition to the

previous technique of stopping after a predetermined number of epochs have been conducted, ANN training can stop after progress toward improving the minimization of the error distance is no longer being achieved. Care here must be taken to ensure a sufficient number of epochs occur between measurements since improvement on each individual epoch is not guaranteed under the back propagation procedure (Weiss, 1991: 101).

Under the Lippmann algorithm, a learning rate η and a momentum term α must be decided upon. Weiss recommends a learning rate of .5 and a momentum term of .9 (Weiss, 1991: 101). Rogers lists an example of using a learning rate of .3 and a momentum rate of .7 (Rogers et al., 1990: 56). According to Weiss, ideally, “one would like to use the largest learning rate that still converges to the minimum solution” (Weiss, 1991: 100). The goal of incorporating a momentum term is to speed the rate of convergence and avoid local minima (Weiss, 1991: 101). Finally, Wiggins recommends a learning rate of approximately .001 (Wiggins, 1991: 14).

Backward propagation is data hungry. Lippmann notes that “in many cases the number of presentations of training data required for convergence has been large (more than 100 passes through all the training data). Although a number of more complex adaptation algorithms have been proposed to speed convergence, it seems unlikely that the complex decision regions formed by multilayer perceptrons can be generated in few trials when class regions are disconnected” (Lippmann, 1987: 18).

Perhaps the most extensive comments on back propagation come from Weiss. He offers a similar algorithm for back propagation and notes that the back propagation algorithm possesses some strong points and some weak points. For example, even the slightest change in net structure may yield vastly different results. Weiss offers some alternatives for improvement. In the algorithm, the programmer has the option of altering the weights after going through the entire training set (after each epoch) or revising after each exemplar. Weiss recommends revising weights after each exemplar, “although revision by epoch may have the stronger theoret-

ical foundation" (Weiss, 1991: 99). Hart concurs with this because it speeds up training, "especially in the early stages" (Hart, 1992: 218). Other suggestions for improvement include the following: presenting the training cases in random order; using biases randomly selected between -.5 and .5; normalizing inputs to numbers between 0 and 1; and repeating training sessions several times with different randomly selected initial weights (Weiss, 1991: 99 - 100).

Another potential weak point of the back propagation technique is the fact that, if enough hidden units are added to a network, one can eventually lower the error distance down to zero. However, the danger here is that of overfitting to the training data. Weiss gives the example that, with the addition of sufficient hidden units, one can get the error distance down to zero even if the sample data has an inherent Bayes error rate of 30% (Weiss, 1991: 103).

Weiss lists several potential problems with the back propagation procedures. He calls it a 'user's nightmare.' Those potential problems include the following: choosing the appropriate learning rate and momentum term, choosing to train by epoch or by pattern (case), finding an effective initial random starting state, and deciding when to stop. Changing any of these parameters may have a 'major' impact upon the results (Weiss, 1991: 108).

Weiss mentions a variation on the standard back propagation procedure which uses ordinary differential equations (ODE) and often yields superior results. This technique eliminates the need to adjust parameters and treats the differential equations as black boxes that can be called on without a detailed understanding of the mathematics occurring inside them (Weiss, 1991: 108).

2.4 Stopping Criteria

An important, yet relatively unexplored area of ANNs is determining when to stop ANN training. The goal of a stopping criteria should be to stop the learning

process of an ANN before the ANN starts overfitting the exemplars (Ramamoorthy, 1989: 136).

Ramamoorthy and Shehkar discuss one method of determining a stopping point. They call for monitoring the classification error rate of a test set in addition to monitoring the classification error on the training set. Inherent in this is the assumption of the training and test sets being independent. As training occurs, the classification error should initially decrease for both sets. Ramamoorthy recommends watching the error of the test set as it decreases. When a general increase in the error classification curve of the test set occurs, it indicates that the training data set is being overfit and that training should cease. The error function has been minimized and this is the stopping point for the learning algorithm. This is referred to as a “transition from [an] underfitted model to overfitting of [the] model” (Ramamoorthy, 1989, 140).

Another criterion which may be monitored during ANN training is the error sum of squares. Using this criteria, the error is computed between the desired output and the ANN output. A key point to remember in using the back propagation algorithm is that the sigmoid function is not capable of providing perfect matches between the desired output and the ANN output. For example, regardless of the value of the input x , the output function

$$y = \frac{1}{1 + e^{-x}}$$

can not possibly give an output of 0 or 1, which is the desired response (Choie, 1991: 723). Therefore, when seeking to minimize the sum of squares for error, ESS , defined as

$$ESS = \frac{1}{2} \sum_i (y_i - d_i)^2$$

(where y_i is the computed output and d_i is the desired output), the sum can never reach 0.

When using *ESS*, the establishment of the critical value of *ESS* at which ANN training should stop is important. For example, assume the goal of ANN training is to train the network until the *ESS* is 0.04. In this case, every exemplar in the training set must be off by less than 0.2 from the desired response for training to terminate. Otherwise, any individual exemplar which is off by a value of 0.2 or higher unilaterally pushes the sum of function *ESS* to greater than 0.04 (because $0.2^2 = 0.04$) regardless of the error in all other exemplars. Therefore, a single exemplar may keep the algorithm from stopping if the stopping criteria is the function *ESS* (Choie, 1991: 724).

Because of these complications caused by one potential exemplar, Choie and others recommend a test which seeks the maximum error for each exemplar of some constant, say .5 (Choie, 1991: 724). They further point out that this stopping criteria, like the rest, has potential problems and should not be used universally. On the other hand, some note that squaring the error seems to lead to overlearning the training set and therefore recommend using the absolute error instead (Hergert, 1992: 980).

Another stopping criteria is proposed by Pan and Chen. They point out that a measure of completeness is the amount by which the weights are changing during each epoch. Therefore, they propose monitoring the following function:

$$E = \sum_{k=1}^m [w_k(t+1) - w_k(t)]^2$$

where m is the total number of weights and w_k is the weight of neuron k for the t th epoch (Pan and Chen, 1992: 360). Pan and Chen do not give a standard for how much weights can change before the optima is reached.

An extension of the Pan and Chen stopping criterion involves observing the average absolute relative weight change WC defined over n exemplars as follows:

$$WC = n^{-1} \frac{\sum_{k=1}^n |w_k(t+1) - w_k(t)|}{|w_k(t)|}$$

Using a third set of data, or a validation set, is another procedure. The validation data set is treated similar to the testing data set in that training ceases when the classification error rate on the validation set increases. Using a validation set in this way was recommended for the case where the training and test data sets contained noise (Hergert, 1992: 980). This thesis study will use the XOR problem and a mesh problem with known data; therefore the validation set will not contain noise. However, the principle of a third data set appears relevant even without considering the addition of noise.

In summary, the literature provides the following different suggestions on functions of the artificial neural network to track when deciding when to terminate ANN training.

- Total absolute error.
- The error sum of squares.
- The largest absolute error.
- Classification error rate for the training set or the testing set.
- Size of the change in weights between epochs.

Additionally, the following stopping criteria will be evaluated.

- A combination of the classification error rate for the training set, the testing set, and the validation set.
- A technique where each potential stopping criterion is a switch, stopping when a sufficient number of switches are turned 'on'.

III. Methodology

This chapter covers the decisions and techniques to be used in this evaluation. Specifically, it covers the following areas: introductory decisions, the problem to be solved, the FORTRAN program, potential stopping criteria to be considered, and evaluation criteria.

3.1 Introductory Decisions

3.1.1 Strategic Decisions. In beginning the project development, some strategic decisions were made regarding performing back propagation using multi-layer artificial neural networks. Those decisions are detailed below.

- Selecting the data. Choices here included using actual or computer generated data. Since it was desired to know whether ANN learning had been successful, a great deal of data was needed. Therefore, the study used random, computer generated data.
- Selecting a data philosophy. Generally, there were two ways to treat the training versus the testing data. First, they could both have been in a larger data set from which the training and testing exemplars were drawn. Alternatively, the study could have used distinct training and testing sets. This study examined both approaches, keeping the training and testing exemplars separate in one part of the initial experiment and randomly assigning exemplars to the training and testing sets during the second part of the initial experiment in an attempt to prevent overlearning or overfitting the data in another part of the initial experiment.
- Evaluation philosophy. In the end, a technique must exist to decide which ANN solution was the 'best.' Alternatives already presented include the classification error rates on various data sets, the largest absolute error, the sum of squared

errors, and the speed of reaching a solution. The study used the classification error rate on a separate validation set. The validation set used was larger than the training and testing sets and is considered to represent the true population.

- Selecting the problems to solve. The study used two problems which are common in the study of ANNs: the Exclusive OR (XOR) problem and a meshed data set problem. These problems were chosen because of their relative simplicity and the large availability of data points.

3.1.2 Tactical Decisions. In addition to the strategic decisions, running the ANN requires some tactical decisions.

- Number of nodes and hidden layers. Both of these factors can affect the training time and the ability of the artificial neural network (ANN). For the purposes of deciding when to stop training, however, the number of nodes and hidden layers must be held constant as a controlled variable. Therefore, the general practice in the literature of having one hidden layer was used. The decision of how many nodes to place on the hidden layer is more arbitrary. As an initial experimental set up, three nodes in the hidden layer were used. For the meshed data set problem, the number of hidden nodes was varied from four to twenty (inclusive for even numbers only).
- Number of training vectors to use. Foley recommended using three times as many training vectors per class as there are features. Additionally, he noted that if the total number of training vectors for a two-class problem is less than twice the number of features, the error rate on the training set will be very close to zero (Rogers et al., 1990: 61). Since the beginning experiment called for two features with one hidden layer, a training set containing 100 exemplars was used. This number safely exceeded Foley's recommendation.
- Setting the learning rate and momentum rates. The current literature does not provide a consensus for these attributes of the ANN. Therefore, a learning

rate of 0.35 as used by those with experience in ANNs such as Rogers (Rogers, et al., 1990: 56) will be implemented. Momentum, on the other hand, was treated differently. Although it offers some advantages in an ANN, its primary attribute is that it allows training to be sped up. Since this study was primarily interested in deciding when to stop training as opposed to how fast the ANN can get to that stopping point, momentum was omitted from the ANN algorithm. Remember additionally that the back propagation algorithm is based upon a form of the steepest descent, which is widely known to converge slowly. Therefore, the back propagation algorithm was expected to be slow and the study was not primarily concerned with the speed of convergence.

- Normalizing the input features. The general consensus in the literature on this question leans toward normalizing the input features to values between -1 and 1. This philosophy was followed. Using the XOR problem, all input features took on values between -1 and 1. If different inputs are used later, they must be normalized outside of the program before input.
- Updating weights after each exemplar or each epoch. Here again, the literature allows either decision to be correct. This study used the technique of updating weights after each exemplar.
- Randomizing the data. ANN training used the technique where the order of the exemplars were randomized in the training set before ANN training. Although the effect of not doing so is unknown, the effect can not be deleterious in any case.

3.2 Problem Selection

This study examines two problem data sets which will be described next.

3.2.1 The Exclusive OR Problem. An investigation of stopping criteria required an abundance of data where the correct output is known. Therefore, the Exclusive OR (XOR) problem was used for the pilot study.

The XOR problem is popular because of its relative simplicity and the ability to generate an abundance of data. It is a more complex region than can be handled by the single perceptron and the two regions can not be separated by a single hyperplane. Essentially, the data are divided as shown in Figure 5. The individual data points

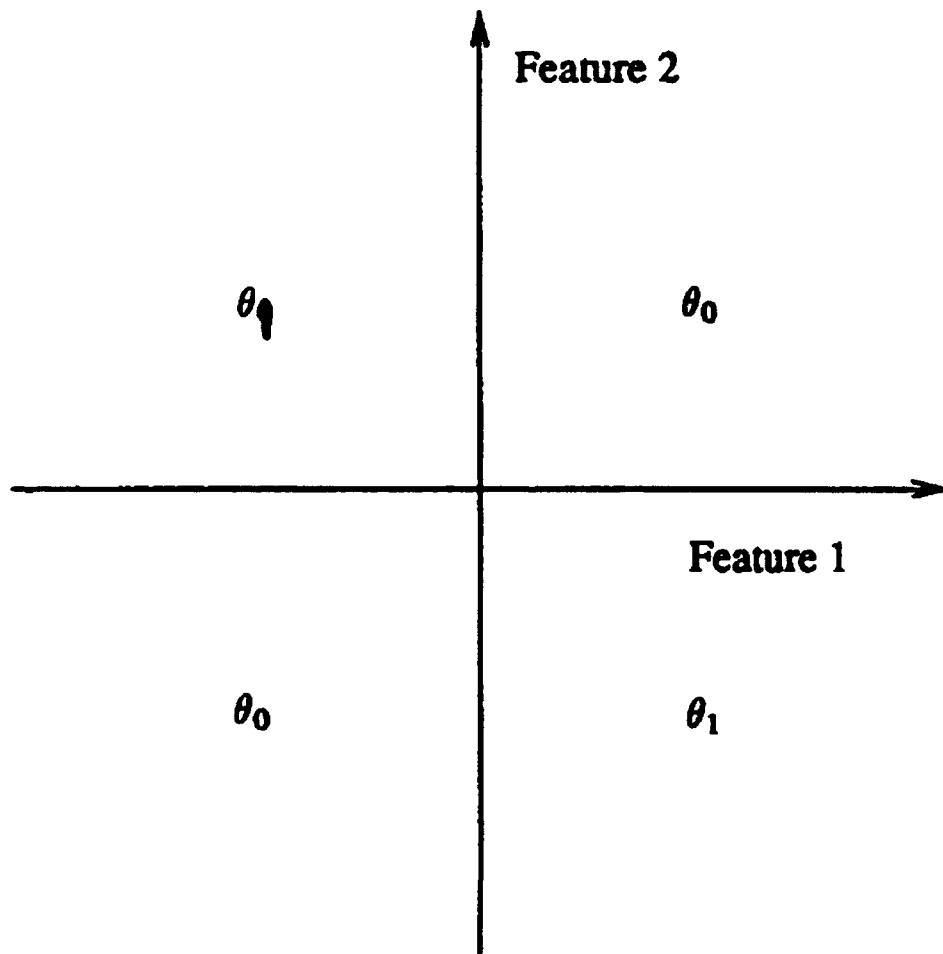


Figure 5. The XOR Problem

are divided based upon the quadrant in which they reside. For example, points in the

area θ_0 are assigned a response of 0 and points in areas θ_1 are assigned a response of 1. Since any point within any of the regions can be used as an exemplar, an infinite number of data points exist for this problem (Rogers et al., 1990: 53).

Since the study used a hypothetical problem for research purposes, ensuring that the proper features were selected was not a concern. The possibility of deleting a relevant feature did not exist unless a random noise variable was added. Likewise, the goal of the thesis was to measure the relative attributes of different stopping criteria and not to find a response surface methodology of the various factors which may affect the learning rate. Therefore, the number of hidden nodes was held constant at three and the learning rate held constant at 0.35.

3.2.2 The Mesh Problem. The second problem examined will be referred to as a mesh problem because it contains a meshed data set. The mesh problem is more complicated than the XOR problem because it involves two regions which can not be separated by two lines. The solution space for each of the outputs for the mesh problem is more complicated and can best be described by a picture. See Figure 6 for a diagram of the two response spaces. Response 1 is the shaded area and the remainder of the space is assigned response 0.

3.3 The FORTRAN Program

The FORTRAN program begins by taking the XOR data and reading each exemplar into the appropriate array for the three individual data sets: the training set, the testing set, or the validation set. Each of these sets is used differently for training and evaluation purposes. The training set is used in training the ANN. The testing set is used primarily for gathering data for the stopping criteria. The validation set is used to represent the population when evaluating the goodness of the proposed solution.

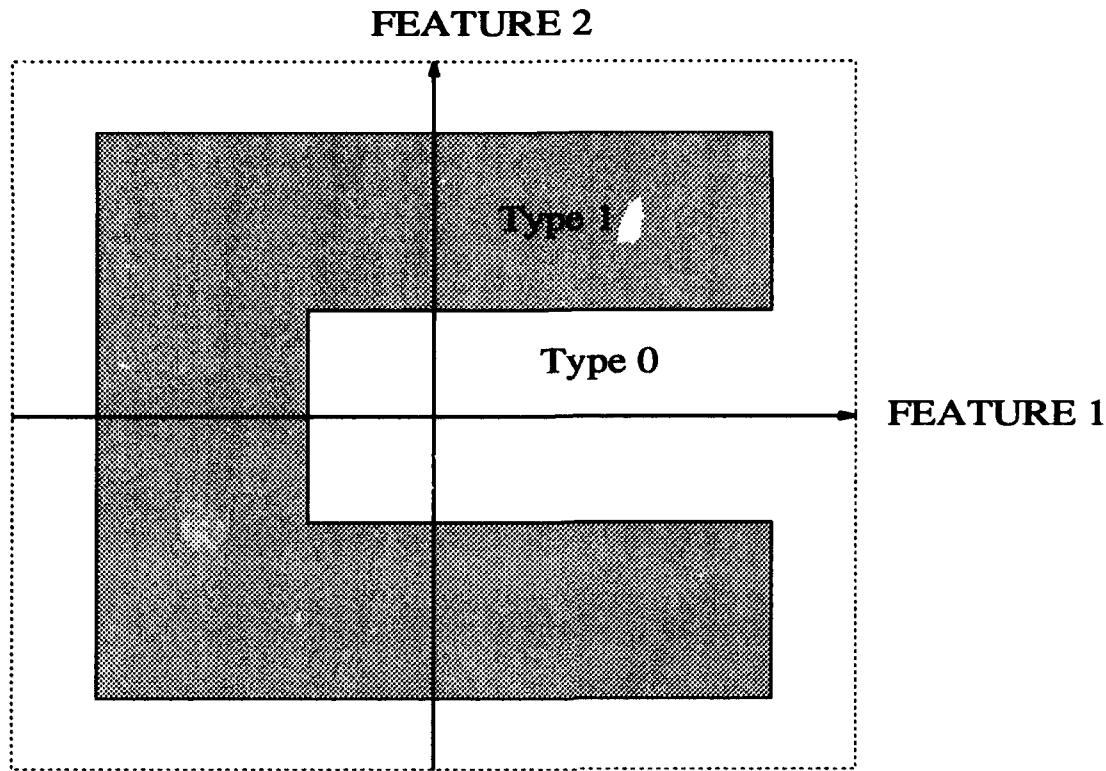


Figure 6. The Mesh Problem

After the data is assigned to the various sets, the ANN begins the learning process. After each epoch, each potential stopping criterion is queried to determine its current level and a new random order of training exemplars is assigned. The process continues for each set of beginning random weights until all stopping criteria have been tracked through the maximum number of epochs. Finally, the program checked to see if a sufficient number of replications of beginning weights have been used. At each replication, new initial random weights are assigned.

When enough replications of the program have been run, the output of each potential stopping criterion is compared to the classification error rate for the validation set as a representation of the output of the ANN on the population. An ideal predictor of when to stop ANN training should cross some threshold or exhibit some

telltale characteristic at the point at which the classification error rate of the validation set is at a minimum. For a flow chart description of the FORTRAN program, see Figure 7.

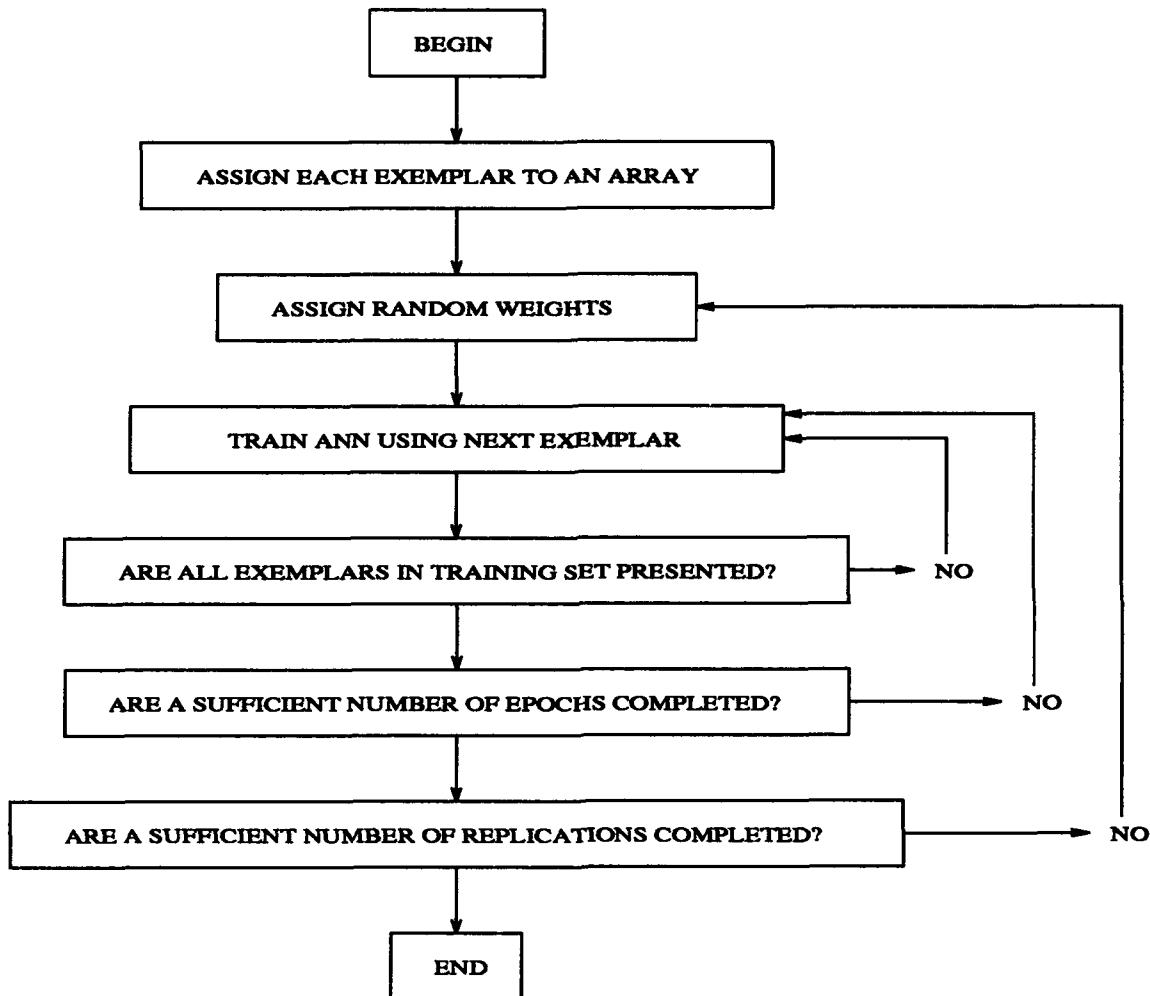


Figure 7. FORTRAN Program Flow Chart

3.4 Stopping Criteria

The essential goal here was to stop training at the optimum point such that the ANN avoided overlearning and reached an acceptable error rate as soon as possible.

Therefore, the study must answer the question of how many times the training data should be presented.

Through reviewing the literature and by considering additional potential areas of study, the following potential stopping criteria were considered as part of this study:

- Total absolute error on the testing set.
- The error sum of squares on the testing set.
- The largest absolute error on the testing set.
- Classification error rate for the training set or the testing set.
- Size of the change in weights between epochs measured specifically in the following four ways: absolute weight change, squared weight change, relative weight change, and mean weight change.
- A combination of the classification error rate for the training set and the testing set as measured by the weighted average error rate.
- A measure where each potential stopping criteria is a switch, stopping when a sufficient number of switches are turned 'on'.

For the mathematical representation of these stopping criteria, please see Appendix B.

3.5 Evaluation Criteria

Should the FORTRAN program indicate potential stopping criteria, a method must exist to determine which stopping criterion is best. On this point, the literature was limited. Therefore, the following strategy was decided upon.

1. Choose the method which resulted in the lowest classification error rate on the validation set.

2. Choose the fastest convergence to a final set of weights. In other words, if all other things were equal, faster was better.

†

IV. Results

4.1 Introduction

This chapter covers experiments conducted using the artificial neural network (ANN) described in Chapter III. Chapter IV uses a chronological sequence of the experiments to lead the reader to the conclusion that the classification error rate, the moving average of the classification error rate, and the total absolute error (all computed using the testing set) are the best indicators of the proper time to terminate ANN training. However, the initial ANN settings must first be enumerated to put the results in the proper context.

4.2 Initial Settings

The initial version of the ANN was trained on the Exclusive OR (XOR) problem using the parameters which follow. It was trained using both the case where the training and testing exemplars were kept separate throughout the experiment and the case where each exemplar was randomly redesignated as belonging to either the training set or the testing set at the beginning of each epoch. Parameters were set as follows:

1. Maximum number of iterations: 1500.
2. Weighted Average Ratio of (training set to testing set): $\frac{5}{5}$ or 1 to 1.
3. Learning rate (η or eta): fixed at 0.35
4. Moving average interval: 5 most recent observations.
5. Size of the training set: 100 exemplars.
6. Size of the testing set: 100 exemplars.
7. Size of the validation set: 600 exemplars.

4.3 Initial Experiment

The goal of the pilot study was to monitor the status of the potential stopping criteria to determine whether any of them change in a manner similar to the classification error rate of the validation set, which was used to represent the true population. Due to data limitations occurring in the real world, the actual classification error rate on the validation set (the population) would be unknown to the ANN programmer. The classification error rate for the validation set recorded during one replication is given in Figure 8. If a potential stopping criterion reaches a threshold

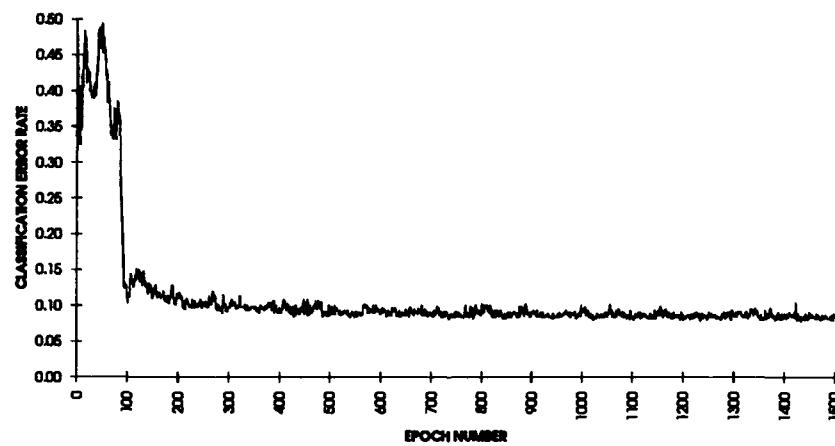


Figure 8. Classification Error Rate on Validation Set

or exhibits a measurable change at the point at which the validation set classification error rate is at a minimum, then it seems reasonable to believe that this stopping criterion may represent an indicator of the proper time to terminate ANN training.

In the initial experiment, the following items were tracked as potential stopping criteria. Mathematical formulations of these criteria are given in Appendix B.

1. Classification error rate on the training set.
2. Classification error rate on the testing set.
3. Classification error rate on a weighted average of the training and testing sets.
4. Moving average classification error rate on the testing set.
5. Total absolute error on the testing set.
6. Error sum of squares on the testing set.
7. Largest absolute error on the testing set.
8. Absolute weight change.
9. Relative weight change.
10. Squared weight change.
11. Mean weight change.

4.3.1 Failed Criteria. Based upon initial runs of the program using the XOR problem, the criteria which follow were judged as relatively weak indicators of the proper time to terminate ANN training and were not selected for further study consideration.

4.3.1.1 Error Sum of Squares. The error sum of squares (on the testing set) of the difference between the ANN output and the desired response yielded decreasing values throughout ANN training. Figure 9 shows the relationship of the error sum of squares value to the epoch in which it was received. However, the resulting differences in error sum of squares values were difficult to evaluate. The difficulty arose from the fact that all of the differences between the desired outputs and the ANN outputs were less than one. Squaring this difference yielded

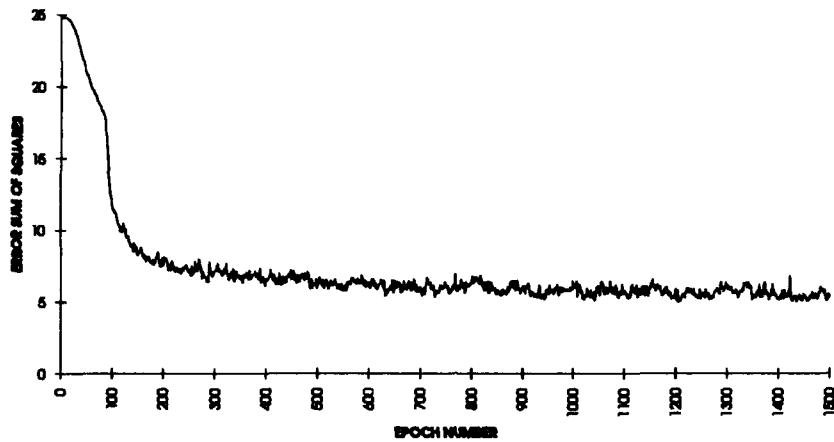


Figure 9. Error Sum of Squares

an even smaller value. While summing these values provided insight as to the status of training, it used smaller (and therefore harder to discriminate) values than the total absolute error stopping criterion which will be discussed later. The error sum of squares was not studied any further because the total absolute error stopping criterion yielded similar, more easily distinguishable results using essentially the same information.

4.3.1.2 Largest Absolute Error. Upon selecting the largest absolute error on the testing set as a potential stopping criterion, it was believed that, as ANN training occurred, the largest absolute error would decrease. While a largest absolute error of less than 0.5 would indicate a 0.0% classification error rate and therefore was an unrealistic standard, expecting the largest absolute error to decrease seemed logical. If the largest absolute error was selected as an indicator for stopping

ANN training, training would be terminated when the largest absolute error got sufficiently small. However, the experiment revealed that, as training occurred and the classification error rate decreased, the largest absolute error increased to values approaching 0.9 as seen in Figure 10. Off line, a slight program modification was

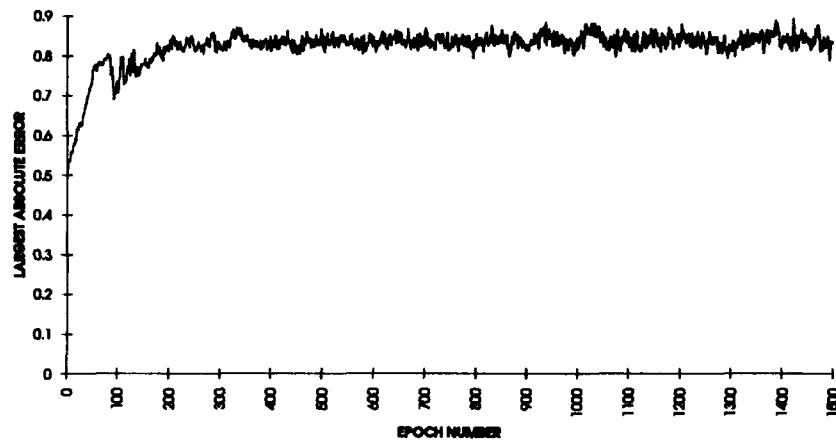


Figure 10. Largest Absolute Error

made to investigate why this occurred. In the modification, the exemplar which yielded the largest absolute error was recorded for each epoch. In nine cases out of ten, the same exemplar ($x_1 = -0.0515647, x_2 = 0.239364$) resulted in the largest absolute error from at least epoch 155 until the end. On average, this occurred sooner than epoch 155. In the tenth case, exemplar $x_1 = -0.883986, x_2 = 0.0143936$ caused the largest absolute error from epoch 44 until the maximum of 1500 epochs was reached. In summary, the ANN appeared to have picked out one exemplar close to an axis (the classification border) and gravitated toward that exemplar as far as

the largest absolute error was concerned. Waiting for one exemplar to be sufficiently incorrect did not seem like a logical reason to terminate a training program which was designed to find the correct answer. Therefore, the largest absolute error was eliminated as a potential stopping criterion.

4.3.1.3 Weighted Average Error Rate. The weighted average error rate was designed in an attempt to compensate for the tendency of some ANNs to overlearn. Overlearning can be detected when the classification error rate on the testing set begins to increase while the classification error rate of the training set continues to decrease. By using part of the training set and part of the testing set, it was expected that an optimal stopping point would occur somewhere around the point at which the increase in the classification error rate of the testing set occurred. However, this expected increase in the classification error rate for the testing set never occurred. Refer to Figure 11. Therefore, for the particular XOR problem used here, using a weighted average error rate provided no additional benefit for this problem and was eliminated as a potential stopping criterion.

4.3.1.4 Absolute Weight Change. The weight change between epochs was monitored because a large weight change would seem to indicate large changes in the ANN function and absence of a local optima. Conversely, a small weight change would seem to indicate a relatively stable function in the current location. However, the resulting absolute weight change between epochs yielded results too inconsistent to be used for determining when to stop training. It was expected the absolute weight change would decrease to a lower level around the ANN optima. However, the absolute weight change varied throughout training in what appeared to be a manner independent of the error classification rate of the validation set. Refer to Figure 12. Therefore, absolute weight change was eliminated as a potential stopping criterion.

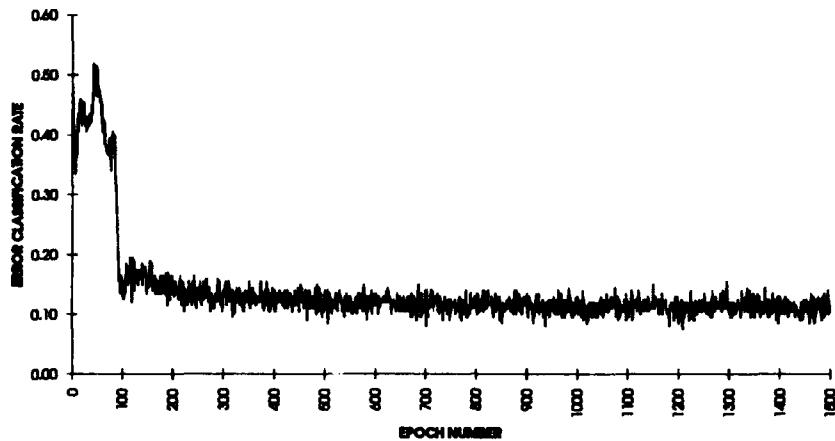


Figure 11. Weighted Average Classification Error Rate

4.3.1.5 Squared Weight Change and Mean Weight Change. The squared weight change and mean weight change were essentially different ways of computing the absolute weight change. Likewise, they yielded inconsistent results and were eliminated as a potential stopping criteria.

4.3.2 Remaining Criteria. After the above potential stopping criteria were eliminated, two criteria remained: the total absolute error on the testing set and the relative weight change.

4.3.2.1 Total Absolute Error. The total absolute error on the testing set as measured by the sum of the absolute value of the difference between the desired response and the ANN output indicated a potential reason for determining when to stop ANN training. The total absolute error (see Figure 13) decreased rapidly early

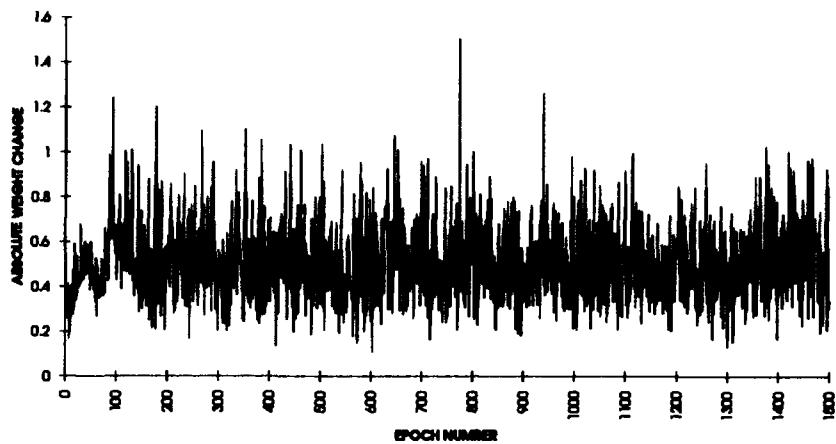


Figure 12. Absolute Weight Change

in training and leveled off at approximately the same epoch as the classification error rate of the validation set leveled off. This mirroring of the classification error rate on the validation set indicated that the total absolute error might be a good indicator of the proper time to terminate training.

4.3.2.2 Relative Weight Change. The relative weight change remained a valid criterion to be tracked, although it was assumed at the time that it showed potential only as an eliminating factor. If the relative weights were changing rapidly, it would seem to indicate that the ANN was not near a local optima, that the function was relatively unstable and changing rapidly, and that ANN training should continue regardless of the levels of the other potential stopping criteria. If, on the other hand, the relative weight change was sufficiently small, ANN training would be allowed to terminate should other factors indicate that a local optima was

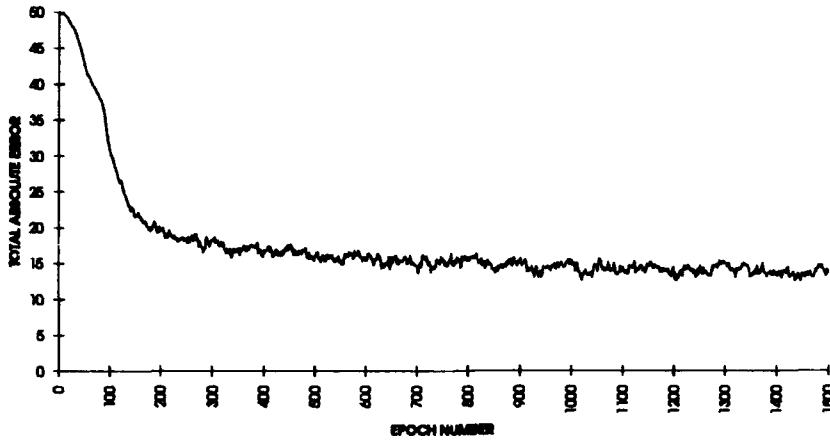


Figure 13. Total Absolute Error

near. Figure 14 shows relative weight change throughout training. Changes or spikes much larger than those indicated here were not uncommon in other cycles of ANN training. Given the high frequency of low relative weight changes early in ANN training, the usefulness of relative weight change as a single indicator of the proper time to terminate ANN training appeared unlikely. However, relative weight change was still tracked due to insufficient evidence to eliminate it completely as a potential stopping criterion at this point.

4.3.2.3 Previously Used Criteria. Training and testing set classification error rates remained valid indicators of the progress when training an artificial neural network. However, classification error rate on the training and testing sets had been previously evaluated as a method of determining when to terminate ANN training. The goal of this study was to investigate new, different reasons to stop

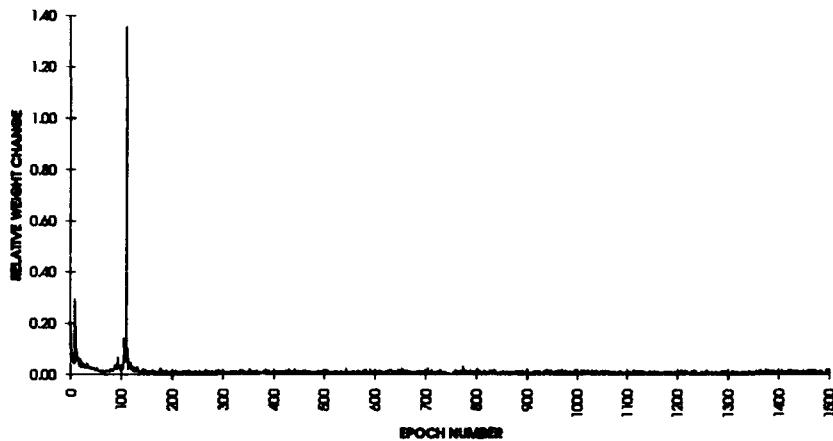


Figure 14. Relative Weight Change

training. Therefore, the study primarily looked at other measures for determining when to stop ANN training.

The moving average error rate is basically a smoother version of the classification error rate of the set (either training or testing) against which it is measured. Therefore, the same logic was applied to the moving average error rate as was applied to the training and testing sets; that is, they have been previously evaluated. All of these previously evaluated criteria remained as something which were tracked, however.

4.3.3 Initial Experiment Summation. Therefore, the following stopping criteria remained valid for continued consideration in the search for new criteria for determining the proper epoch at which to terminate ANN training.

1. Total absolute error.

2. Relative weight change.

In summing up the initial experiment, two additional areas must be covered. First, recall that the maximum epoch setting for the initial experiment was 1500 epochs. By observing the classification error rate of the validation set over ten cycles of 1500 epochs each, it was observed that no significant improvement occurred after 600 epochs (see Figure 8). Therefore, a maximum of 600 epochs was used for future experiments given the current values of η (or learning rate) and the current number of ANN hidden nodes and layers.

Finally, recall that the initial experiment included an evaluation of the differences between using separate training and testing sets and randomly assigning an exemplar to either the training or testing set at the beginning of each epoch. This paper will discuss this issue by using the total absolute error results, which were typical of the output received in all of the other potential stopping criteria categories.

When deciding when to stop ANN training, a consistent output from a potential stopping criterion is needed for that criterion to yield a consistent point at which it indicated a time to stop training. The random assignment of exemplars failed to meet this requirement. Outputs from the measured characteristics varied widely using random exemplar assignment. For example, while a total absolute error of between fifteen and twenty appeared to coincide with the occurrence of a minimum classification error rate for the validation set in every case when the training and testing sets were kept separate, the total absolute error never reached this threshold in some of the cases where the exemplars were randomly assigned at the beginning of each epoch. If a standard were set using the random assignment case, it would not be reached consistently. Similar results were received for other potential stopping criteria. Therefore, random exemplar assignment was eliminated and future experiments included only the case where the training and testing sets were kept separate

throughout training. Recall, however, that this was expected. The random exemplar assignment technique was designed in an attempt to compensate for overlearning. Since overlearning was not observed and the above inconsistent function outputs did occur, it was decided to discontinue the practice of random exemplar assignment. The practice of random exemplar assignment may still be useful should overlearning occur.

4.4 Second Experiment

Using the output from the first experiment and comparing the classification error rate of the validation set with the total absolute error and the relative weight change, certain tendencies of ANN stopping criteria were noted. First, the classification error rate on the validation set appeared to reach a minimum around the time that the total absolute error was approximately 20. A total absolute error of 20 in this case equates to an average absolute error of 0.2 because 100 exemplars were used in the training set. The second tendency noted was that relative weight changes in excess of five percent appeared significant. Here, significant meant that the ANN function did not appear to be stable in areas where the relative weight change exceeded five percent. Therefore, an experiment was designed around these points to test differing levels of these two potential stopping criteria on the ANN responses. Specifically, an experiment was designed to record the classification error rate on the validation set and the speed of reaching a solution (as measured by the epoch at which a simulated solution was selected) at varied levels of the two remaining potential stopping criteria. Results of this experiment follow in two parts.

4.4.1 Single Stopping Criterion. For the first half of the second experiment, each of the two remaining potential stopping criterion were treated individually. That is, when the level of either reached a given threshold for that potential stopping criteria, it would serve as a signal to terminate ANN training for that criterion and threshold level only. At this termination point, the classification error rate on the

validation set and the current epoch were recorded. Using three levels for each potential stopping criterion, nine total results would be explored.

4.4.1.1 Total Absolute Error. Under the single stopping criterion portion of the experiment, ANN training was terminated when the total absolute error reached the threshold levels of 15, 20, and 25. Total absolute error was defined as the sum of absolute values of the difference between the ANN output and the desired output. Results can be found in Figure 15, Figure 16, and Table 1. Both the

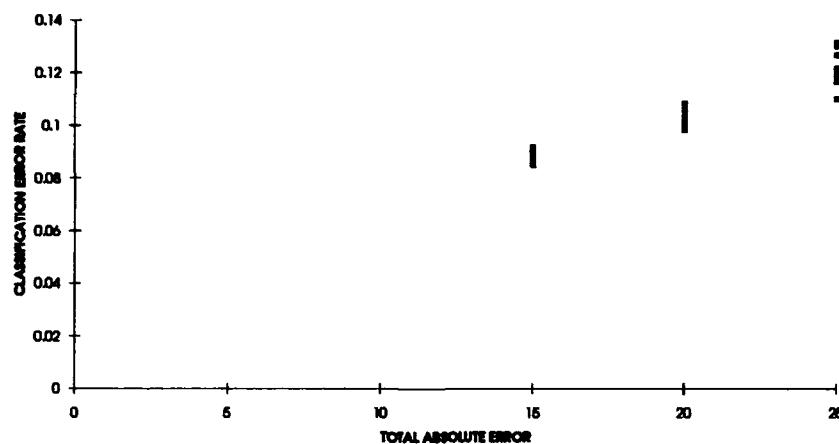


Figure 15. Second Experiment: Classification Error Rate Versus Total Absolute Error

classification error rate on the validation set and the total absolute error decreased as training occurred. These results were expected and they appeared consistent with Figure 8 and Figure 13.

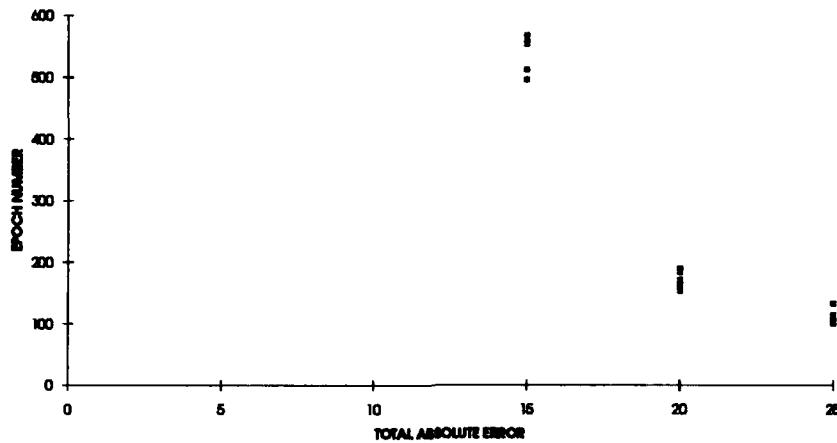


Figure 16. Second Experiment: Completion Epoch Versus Total Absolute Error

These results indicated that as the number of epochs increased, total absolute error on the testing set decreased and the classification error rate on the validation set decreased. This appeared to be consistent with the theory that the total absolute error might be an indicator of when to terminate ANN training. A key remaining question was whether total absolute error was an indicator of classification error rate, and therefore a reason to terminate training, or whether the two characteristics just happened to move together. The possibility that they may have just moved together may be seen in Figure 13, where the total absolute error continued to decrease slightly even after epoch 600, while Figure 8 showed that no significant change in the classification error rate occurred after epoch 600.

4.4.1.2 Relative Weight Change. In this section of the experiment, ANN training was terminated when the relative weight change reached the threshold

| Threshold | Number of Occurrences | Mean Epoch | Epoch Standard Deviation | Mean Error Rate | Error Rate Standard Deviation |
|-----------|-----------------------|------------|--------------------------|-----------------|-------------------------------|
| 15.0 | 6 | 542 | 30 | 0.0886 | 0.002 |
| 20.0 | 9 | 170 | 14 | 0.1033 | 0.003 |
| 25.0 | 9 | 109 | 11 | 0.1230 | 0.007 |

Table 1. Second Experiment: Total Absolute Error

levels of 0.01, 0.05, and 0.09. Results can be found in Figure 17, Figure 18, and Table 2.

| Threshold | Number of Occurrences | Mean Epoch | Epoch Standard Deviation | Mean Error Rate | Error Rate Standard Deviation |
|-----------|-----------------------|------------|--------------------------|-----------------|-------------------------------|
| 0.01 | 10 | 105 | 10 | 0.1780 | 0.110 |
| 0.05 | 10 | 12 | 14 | 0.4123 | 0.057 |
| 0.09 | 10 | 7 | 6 | 0.4340 | 0.028 |

Table 2. Second Experiment: Relative Weight Change

These results indicated that, as the relative weight change threshold decreased, the number of epochs required to reach a solution increased and the classification error rate decreased. Overall, this seemed to indicate that the relative weight change should remain valid as an indicator of when to terminate ANN training. Relative weight change at the lowest level (less than 0.01) has a classification error rate of nearly 18%, but the chance of an outlier was relatively large, with two appearing in this case. Also note that the occurrence of the outliers caused the variance to increase as the mean classification error rate decreased.

Due to the relatively high classification error rate (when compared to that achieved by the total absolute error on the testing set criterion) and the relatively high variance of the classification error rate caused by the occurrence of outlier cases,

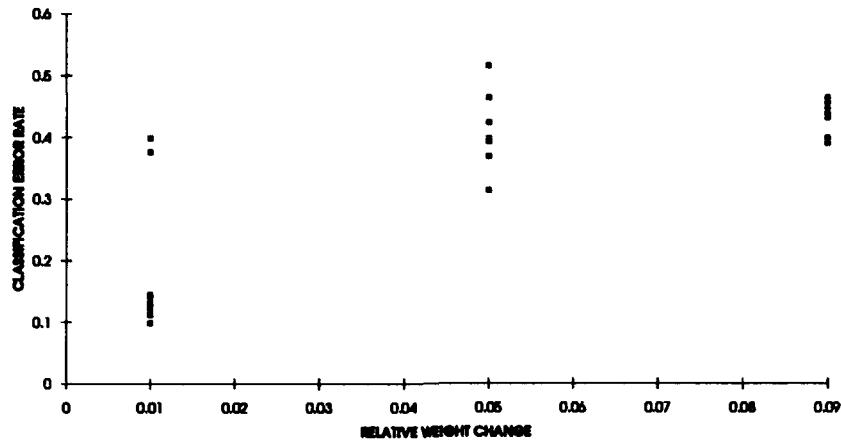


Figure 17. Second Experiment: Classification Error Rate Versus Relative Weight Change

a decision was made to continue to track the relative weight change, but only as an eliminating factor. By looking at the raw data, using the relative weight change as a primary determinant of stopping ANN training appeared unacceptable. Levels of relative weight change of less than one percent were rare and appeared to be mainly a hit or miss proposition which was searching for extremely small differences. Relative weight changes of less than one percent did occur, but they occurred randomly and were too inconsistent to indicate a proper epoch at which to terminate ANN training. Therefore, relative weight change remained under consideration only as an eliminating criterion.

4.4.2 Two Phase Stopping Criterion. To further determine the impacts of the relative weight change and the total absolute error as measurements of stop-

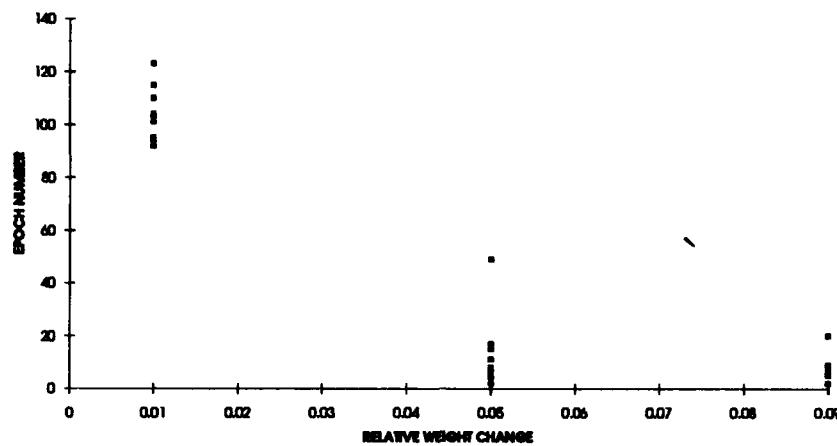


Figure 18. Second Experiment: Completion Epoch Versus Relative Weight Change

ping criteria, a two step stopping point criterion was implemented. Here, the total absolute error stopping criterion was varied from 15 to 25 in five uniform steps of 2.5 each and the relative weight change stopping criteria was varied from 0.01 to 0.09 in five uniform steps of 0.02 each. Both criteria had to be met before the ANN would recognize a requirement to terminate training. To evaluate these potential stopping criteria over the ten replications, the program measured a response of the mean classification error rate (see Figure 19) and the time to reach a recommended solution as determined by the mean current epoch at the time both thresholds were met (see Figure 20). The levels of total absolute error and relative weight change used here were selected heuristically from those lower levels occurring during ANN training. When comparing Figure 19 and Figure 20, note that both the axis for total absolute error and the axis for relative weight change were inverted between

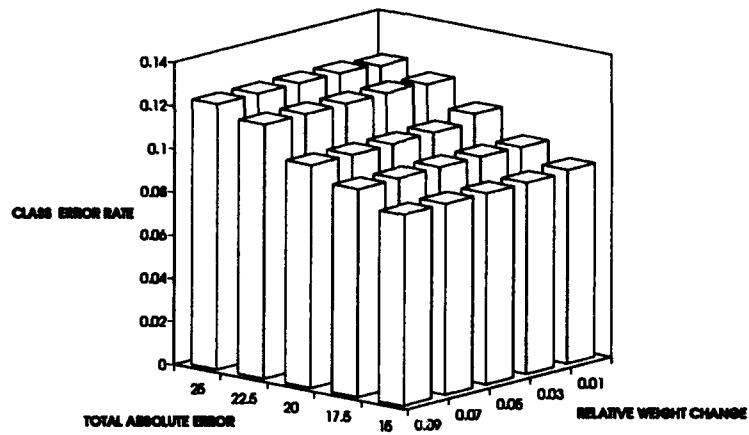


Figure 19. Second Experiment: Classification Error Rate Using Two Criteria

the two figures. This was done for presentation purposes to show bars which would otherwise be hidden in the rear of the figure.

Figure 19 and Figure 20 indicate the relative unimportance of the relative weight change criterion. As the relative weight change was varied in this experiment, the mean classification error rate and the mean completion epoch remained relatively stable. The main determinant of the classification error rate and the epoch of completion in this double stopping criteria experiment was the threshold level of the total absolute error.

4.5 *Third Experiment*

The second experiment showed that total absolute error was the only remaining factor which could be used as a determinant for stopping ANN training in this

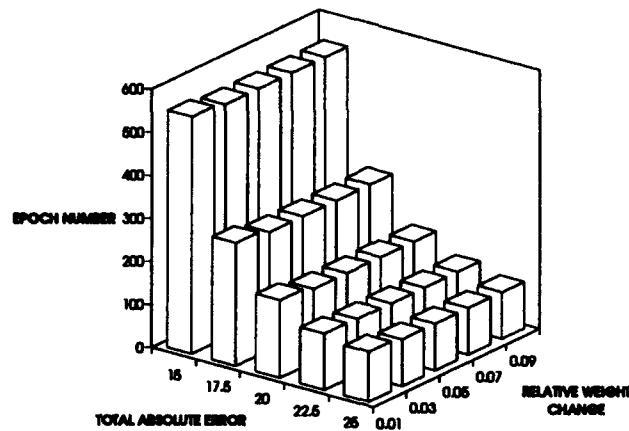


Figure 20. Second Experiment: Completion Epoch Using Two Criteria

particular network design. However, the limits of how low total absolute error would go within the 600 epoch limit established here were not yet known. The second experiment only tested total absolute error at five levels between 15 and 25. Therefore, a third experiment was designed to provide a closer examination of total absolute error. In particular, a program modification was made to find the resulting classification error rate and epoch of completion when the levels of stopping ANN training for the total absolute error were set at whole number increments of 0 to 20.

4.5.1 The Total Absolute Error Function. The results of this experiment indicated that, through chance, the level of fifteen which was selected for the second experiment was indeed the lower limit for total absolute error in this particular network design. The curve was decreasing, asymptotically approaching values just less than 15 (see Figure 21 and Figure 22). In fact, the total absolute error decreased

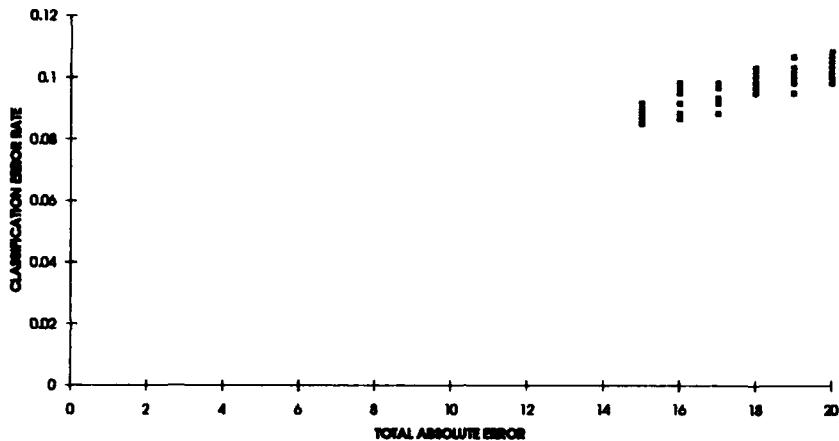


Figure 21. Third Experiment: Classification Error Rate Versus Total Absolute Error

to the level of 15 in only six of the ten test cases in this experiment. No observations occurred at the experimental levels of 14 or lower.

4.5.2 The Total Absolute Error Conclusions. Within the 600 epoch limitation resulting from the observation that the classification error rate for the population (the validation set in this case) did not decrease beyond that epoch, the lowest that total absolute error went for this particular experiment was 15. Table 3 shows the details of the total absolute function at the various levels throughout training. As the total absolute error decreased, the classification error rate and the variance of that classification error rate also both decreased. Therefore, a higher probability of selecting an ANN which had both a smaller true classification error rate and a

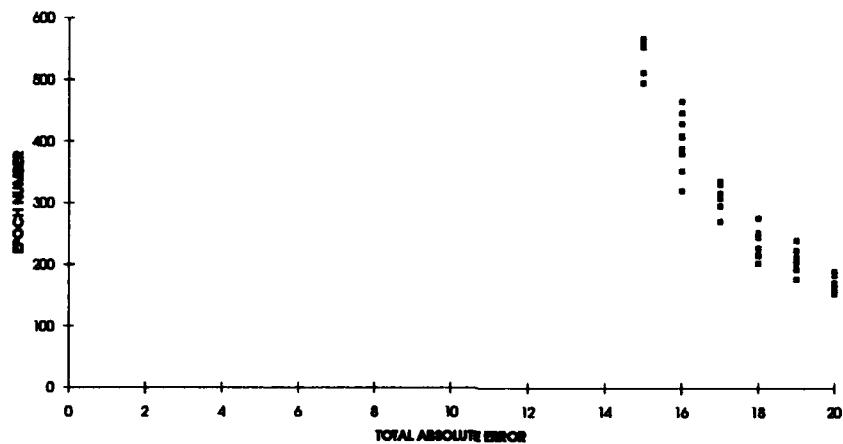


Figure 22. Third Experiment: Completion Epoch Versus Total Absolute Error

smaller variance of the classification error rate was achieved by selecting a random set of ANN weights based upon the lowest total absolute error of the testing set.

Perhaps as significant as noting the behavior of the total absolute error function when the threshold levels in Figure 21 were reached was noting how the total absolute error function reacted when the threshold levels were not reached. Notice in Table 3 that the threshold level was reached in nine out of ten replications. In the replication in which no threshold levels were reached, the total absolute error function remained greater than 33 throughout 600 epochs of training and the final classification error rate for the validation set was approximately 30%. The results indicated that the classification error rate on the validation set was not at the lowest levels if the total absolute error function was not at the lowest level. Figure 13 showed the total absolute error function for a replication which met the threshold level of 15. For

| Threshold | Number of Occurrences | Mean Epoch | Epoch Standard Deviation | Mean Error Rate | Error Rate Standard Deviation |
|-----------|-----------------------|------------|--------------------------|-----------------|-------------------------------|
| 15 | 6 | 542 | 30 | 0.0886 | 0.002 |
| 16 | 9 | 400 | 45 | 0.0935 | 0.004 |
| 17 | 9 | 311 | 19 | 0.0937 | 0.003 |
| 18 | 9 | 238 | 22 | 0.0991 | 0.003 |
| 19 | 9 | 205 | 19 | 0.1004 | 0.003 |
| 20 | 9 | 170 | 14 | 0.1033 | 0.003 |

Table 3. Third Experiment: Total Absolute Error

an examination of the total absolute error functions which did not meet all of the threshold levels of Table 3, see Appendix C.

4.6 *Mesh Problem Experiment*

4.6.1 *Mesh Problem Set Up.* A sequence of steps to this point had led to a solution for the XOR problem, but the question remained whether these same steps could assist in solving a different problem. As noted earlier, the mesh problem involved a more complicated space for the two classes. Therefore, the ANN was allowed to train for a greater number of epochs. After inconclusive results were reached using a network with a maximum number of epochs set at 1500, the ANN was allowed to train for 3000 epochs. An example of the classification error rate received during one replication is given in Figure 23. The classification error rate in Figure 23 is formed from an evenly weighted average of the classification error rate of the training and testing sets for one of the ten replications. A weighted average was used because, when attempting to use an artificial neural network to classify data, the classification of the population would be unknown. Therefore, the ANN was only given as much data as was considered known in the problem. The validation set data was treated as an unknown population.

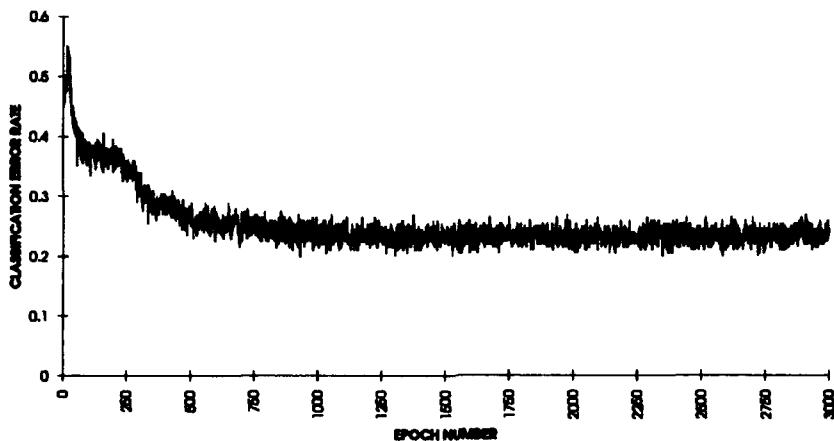


Figure 23. Mesh Problem Classification Error Rate

Figure 23 resulted in the assumption that no further learning occurs after epoch 2000. However, the ANN was allowed to train up through epoch 3000 for evaluation purposes.

4.6.2 Mesh Problem Results. Mesh problem results are given in a format similar to that used for the XOR problem. A comparison of the epochs required to obtain a solution and the classification error rate are given in Figure 24 and Figure 25 respectively. Table 4 contains the average data results.

Figure 24 and Table 4 illustrate a key finding regarding the total absolute error on the testing set function. When the lowest total absolute error occurred (at a value of approximately thirty), the average classification error rate on the validation set was greater than the average classification error rate recorded at a total absolute error value of approximately thirty-one. This demonstrated that simply terminating

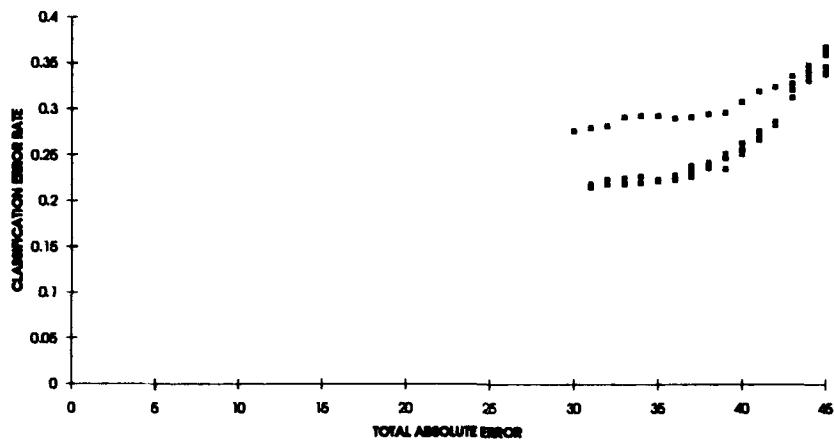


Figure 24. Mesh Problem: Classification Error Rate Versus Total Absolute Error

ANN training at the lowest recorded value of the total absolute error on the testing set did not guarantee that the ANN would yield the lowest classification error rate on the validation set.

Using the total absolute error technique of deciding upon the point at which to stop ANN training resulted in a higher classification rate for the mesh problem than for the XOR problem. Given the more complicated class divisions of the mesh problem, this was not unexpected. Figure 26 gives the solution space of the ANN output to visually quantify the mesh output results. The classification error rate of this particular network design never decreased below 20%. In fact, in only three of the ten replications did the classification error rate on the validation set decrease below 30%. The classification error rate of the ANN design seen in Figure 26 was 22.83% and was achieved after 50,000 epochs.

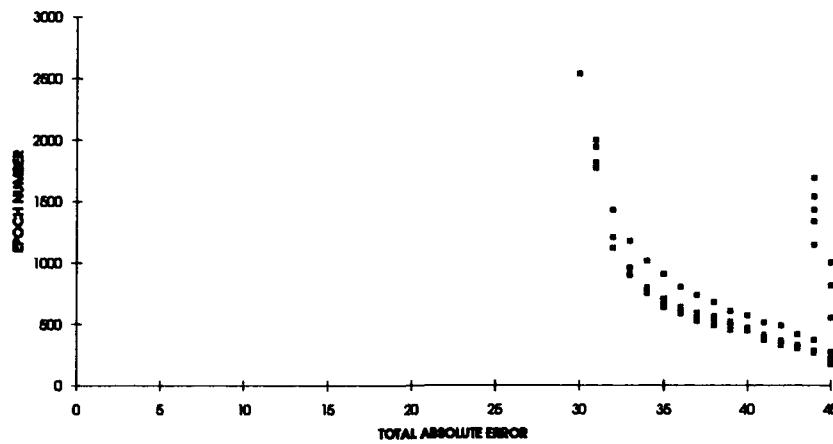


Figure 25. Mesh Problem: Completion Epoch Versus Total Absolute Error

Since the other replications yielded similar solution spaces, it appeared that an ANN with three hidden nodes was insufficient to map the many corners found in this particular mesh design. Neither the total absolute error nor the classic techniques (such as stopping training at the lowest level of the testing set classification error rate) mapped the solution closely. All stopping criteria techniques failed to detect the corners of the meshed data set. The ANN proposed solution seemed to encircle the largest mass as opposed to attempting to search out the corners of the solution space.

Therefore, it was decided to test the ANN with a different number of hidden nodes to see if more hidden nodes would allow the ANN to 'get around the corners' of the mesh problem. An ANN with eight hidden nodes was trained for up to 15,000 epochs. A graph of the ANN output resulting from this experiment is given in

| Threshold | Number of Occurrences | Mean Epoch | Epoch Standard Deviation | Mean Error Rate | Error Rate Standard Deviation |
|-----------|-----------------------|------------|--------------------------|-----------------|-------------------------------|
| 30.0 | 1 | 2535 | N/A | 0.2767 | N/A |
| 31.0 | 5 | 1891 | 96 | 0.2290 | 0.029 |
| 32.0 | 5 | 1232 | 115 | 0.2337 | 0.027 |
| 33.0 | 5 | 964 | 121 | 0.2360 | 0.031 |
| 34.0 | 5 | 826 | 107 | 0.2383 | 0.031 |
| 35.0 | 5 | 715 | 108 | 0.2367 | 0.032 |
| 36.0 | 5 | 650 | 88 | 0.2387 | 0.029 |
| 37.0 | 5 | 590 | 84 | 0.2437 | 0.027 |
| 38.0 | 5 | 554 | 74 | 0.2500 | 0.025 |
| 39.0 | 5 | 511 | 59 | 0.2567 | 0.024 |
| 40.0 | 5 | 466 | 59 | 0.2673 | 0.023 |
| 41.0 | 5 | 415 | 57 | 0.2813 | 0.022 |
| 42.0 | 5 | 376 | 62 | 0.2927 | 0.018 |
| 43.0 | 5 | 334 | 45 | 0.3227 | 0.010 |
| 44.0 | 10 | 861 | 611 | 0.3410 | 0.006 |
| 45.0 | 10 | 390 | 294 | 0.3572 | 0.010 |

Table 4. Mesh Problem: Total Absolute Error

Figure 27. This solution space more closely maps the true solution space given earlier in Figure 6. Under this revised network, the classification error rate on the validation set was able to decrease to less than 30% in all ten replications and obtained levels of less than 20% in seven of the ten replications. The mesh solution space graph given in Figure 27 resulted in a classification error rate of 9% for the validation set.

4.6.3 Varying the Number of Hidden Nodes. The next logical step was to vary the number of hidden nodes in the ANN design. As the number of hidden nodes was varied, a comparison was made of the classification error rate of the solution occurring at the lowest level of the total absolute error to the classification error rate at the solution occurring at the lowest levels of the previously evaluated stopping criteria (such as the classification error rate of the testing set). A closure in the form of a recommended method by which to determine the proper time to terminate ANN

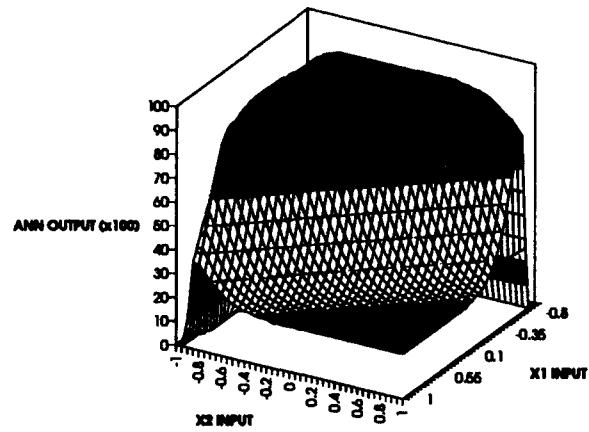


Figure 26. Mesh Solution Space: Three Hidden Nodes 50,000 Epochs

training would result if one stopping criterion proved itself superior by consistently recommending the lowest classification error rate of the validation set. A relatively small variance of the classification error rate for any stopping criterion selected at this step would further support its selection as an optimal stopping criterion.

The number of hidden nodes was varied at levels of all even numbers between four and twenty for 15,000 epochs. Potential stopping criteria measures compared to the minimum total absolute error included the following: classification error rate on the training set, classification error rate on the testing set, a evenly weighted average of the classification error rate of the training and testing sets, and a moving average of the classification error rate on the testing set over the most recent five epochs. Full results of the experiments for the ten replications at each selected number of hidden nodes can be found in Appendix D.

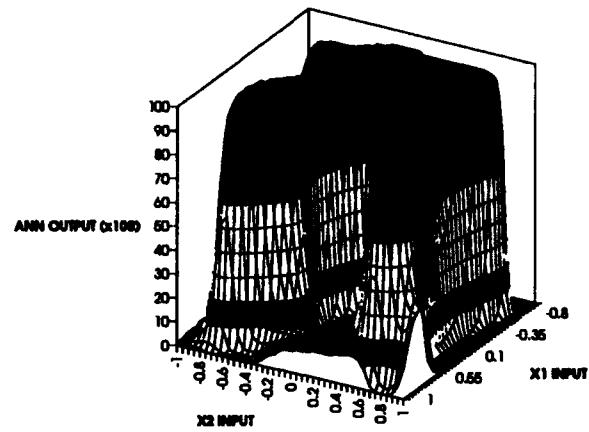


Figure 27. Mesh Solution Space: Eight Hidden Nodes at 9,000 Epochs

A detailed review of Appendix D reveals a complication in the results. A simple average was not a fair comparison. For example, if the classification error rate on the training set for a given replication were to remain much higher than that for the other replications, common sense indicated that that particular set of ending ANN weights should not be selected. Therefore, fairness dictated that these weights not be counted when computing averages. Additionally, a comparison across the different metrics revealed that some sets of starting weights led to a relatively low classification error rate on the validation set regardless of the stopping criterion used and some starting weights led to a relatively high classification error rate across all of the potential stopping criteria. This seemed to indicate an advantage of looking at more than one criterion when attempting to determine when to terminate ANN training.

Therefore, the 'obvious' outliers (indicating weights not moving toward the global optima) had to be eliminated. This section of the experiment set up a heuristic for distinguishing between those points 'good' enough to be considered and those points so 'poor' that they should be eliminated. The following heuristic was used.

1. Select the 'best' level within each potential stopping criterion. The best level was defined as the lowest total absolute error or the lowest classification error rate for the training set, testing set, and weighted average and moving average criteria. Select at least two potential points because of the weakness of selecting only one point as indicated in Figure 21 where the lowest total absolute error did not indicate the lowest classification error rate on the validation set.
2. Select approximately a 2% to 4% rate window from the 'best' classification error rate (2 to 4 in absolute value with respect to total absolute error). Actual selection depended upon the grouping of the output. The goal was to obtain a set of points which contained the best classification error rate which would be obtained if a given stopping criterion was used.
3. Using the selected replications, compute the mean and standard deviation of the classification error rate on the validation set.

4.6.4 Results: Varying the Number of Hidden Nodes. Using the above rules, the resulting classification error rates at each of the various hidden nodes tested are summarized in Table 5.

Table 5: Mesh Problem: Selected Solutions

| Stopping Criterion | Average Classification Error | Standard Deviation of Classification Error |
|---------------------------|------------------------------|--|
| Four Hidden Nodes | | |
| Training Set | 0.2294 | 0.0142 |
| Testing Set | 0.2217 | 0.0236 |
| Weighted Average | 0.2204 | 0.0025 |
| Moving Average | 0.2255 | 0.0187 |
| Total Absolute Error | 0.2230 | 0.0263 |
| Six Hidden Nodes | | |
| Training Set | 0.1588 | 0.0270 |
| Testing Set | 0.1570 | 0.0367 |
| Weighted Average | 0.1508 | 0.0351 |
| Moving Average | 0.1458 | 0.0339 |
| Total Absolute Error | 0.1479 | 0.0320 |
| Eight Hidden Nodes | | |
| Training Set | 0.1267 | 0.0390 |
| Testing Set | 0.0967 | 0.0118 |
| Weighted Average | 0.0992 | 0.0082 |
| Moving Average | 0.1000 | 0.0094 |
| Total Absolute Error | 0.1000 | 0.0071 |

Table 5: Mesh Problem: Selected Solutions (continued)

| Stopping Criterion | Average Classification Error | Standard Deviation of Classification Error |
|-----------------------|------------------------------|--|
| Ten Hidden Nodes | | |
| Training Set | 0.0894 | 0.0386 |
| Testing Set | 0.0861 | 0.0067 |
| Weighted Average | 0.0917 | 0.0058 |
| Moving Average | 0.0900 | 0.0033 |
| Total Absolute Error | 0.0883 | 0.0000 |
| Twelve Hidden Nodes | | |
| Training Set | 0.1253 | 0.0322 |
| Testing Set | 0.0933 | 0.0101 |
| Weighted Average | 0.0944 | 0.0035 |
| Moving Average | 0.1025 | 0.0059 |
| Total Absolute Error | 0.0817 | 0.0044 |
| Fourteen Hidden Nodes | | |
| Training Set | 0.1504 | 0.0195 |
| Testing Set | 0.1333 | 0.0284 |
| Weighted Average | 0.1278 | 0.0231 |
| Moving Average | 0.1194 | 0.0210 |
| Total Absolute Error | 0.1183 | 0.0176 |

Table 5: Mesh Problem: Selected Solutions (continued)

| Stopping Criterion | Average Classification Error | Standard Deviation of Classification Error |
|------------------------------|------------------------------|--|
| Sixteen Hidden Nodes | | |
| Training Set | 0.1381 | 0.0288 |
| Testing Set | 0.1133 | 0.0145 |
| Weighted Average | 0.1120 | 0.0239 |
| Moving Average | 0.0971 | 0.0103 |
| Total Absolute Error | 0.1100 | 0.0218 |
| Eighteen Hidden Nodes | | |
| Training Set | 0.1254 | 0.0146 |
| Testing Set | 0.0950 | 0.0180 |
| Weighted Average | 0.0977 | 0.0163 |
| Moving Average | 0.0937 | 0.0122 |
| Total Absolute Error | 0.0900 | 0.0115 |
| Twenty Hidden Nodes | | |
| Training Set | 0.1117 | 0.0234 |
| Testing Set | 0.0850 | 0.0153 |
| Weighted Average | 0.0906 | 0.0154 |
| Moving Average | 0.0872 | 0.0186 |
| Total Absolute Error | 0.0833 | 0.0203 |

The actual impact of each of the examined potential stopping criteria can best be seen in a graph of the two standard deviation dispersion area of the classification error rate which would have been obtained if the lowest level of each stopping criteria were used. What follows is a graph for each ANN design as the number of hidden nodes was varied at even numbers from four to twenty (inclusive). The rationale for this decision was that the user must first make a design decision, then train the network to the lowest level for the selected stopping criterion. Next, a different design could be chosen before conducting training again. Only after the designs had been trained to an optimal level would a decision be made as to the appropriate ANN design. Therefore, the only appropriate comparison between the examined potential stopping criteria occurred when the number of hidden nodes was held constant. See Figure 28 through Figure 36 for a graphical comparison of the stopping criteria for each respective level of hidden nodes.

Given this constraint of looking at each figure separately, the goal was to determine whether any of the remaining stopping criteria consistently gave the lowest classification error rate across all of the ANN designs. The expected range over which this classification error rate would vary was also considered important. A lower variance of the classification error rate of any selected stopping criterion would further support its selection as an optimal stopping criterion. Specifically, given the earlier promise of the total absolute error stopping criterion as exhibited during the examination of the XOR problem, the question was whether or not the total absolute error would again lead to the lowest classification error rate with the minimum variance.

Comparing the diagrams, total absolute error compared favorably with the previously used criteria. In other words, it does not do any worse than the previously used criteria. However, total absolute error did not dominate those criteria such that choosing among the weights corresponding to the lowest total absolute error guaranteed the lowest classification error rate. By using the total absolute error

to select a point to terminate ANN training, the resulting error classification rate was essentially the same as that obtained by using the classification error rate on the testing set, the weighted average classification error rate, or the moving average classification error rate (on the testing set) stopping criteria to terminate ANN training. However, note that the weighted average classification error rate consisted partially of the classification error rate on the testing set, which tended to drift higher as the number of hidden nodes increased.

A final point to remember regarding Figure 28 through Figure 36 is that the actual classification error rate of the population (the validation set for purposes of this study) would not be known for the general case. In this study, perfect knowledge was available and, using that perfect knowledge, an ANN design of either eight, ten, or twelve hidden nodes appeared optimal. This was based upon two facts: the classification error rate and the variance of that classification error rate were lower. Using the total absolute error as the means of selecting the point at which to terminate ANN training in these three situations would have resulted in the lowest classification error rate and variance of the classification error rate in two of the three cases.

For a different comparison of the output of the mesh problem as the number of hidden nodes was varied, see Figure 37 through Figure 41. These figures show the change in the classification error rate for each potential stopping criterion as the number of hidden nodes in varied at even numbers between four and twenty (inclusive). Recall that the mesh problem could ideally be separated by eight bounding hyperplanes. From these results, the following were noted:

- Observing across the figures, all functions demonstrated to an 'S' shaped curve of the classification error rate on the validation set. The classification error rate decreased as the number of number of hidden nodes was increased from four to eight. Next, the classification error rate remained at its lowest level for when eight, ten, or twelve hidden nodes were used. From fourteen to twenty

hidden nodes, the classification error rate increased and then decreased. Using the results of these figures, an ANN consisting of eight, ten, or twelve hidden nodes would be selected.

- At the preferred design of eight, ten, or twelve hidden nodes, a lower variance of the resulting classification error rate on the validation set was observed.
- The bottom line was that the ideal ANN had a logical interpretation: using approximately eight to twelve hidden nodes resulted in the lowest mean error classification error rate on the validation set. Additionally, this ANN termination point also exhibited the lowest variance of the resulting classification error rate on the validation set.

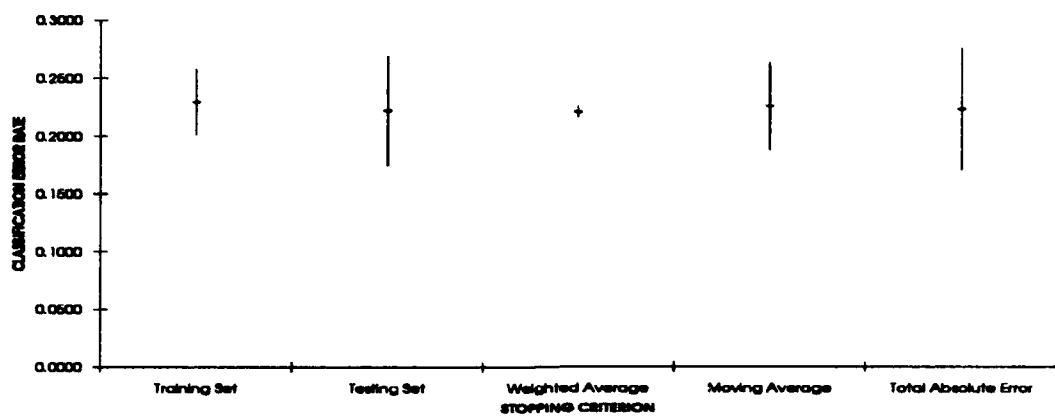


Figure 28. Mesh Classification Error Rate: Four Hidden Nodes

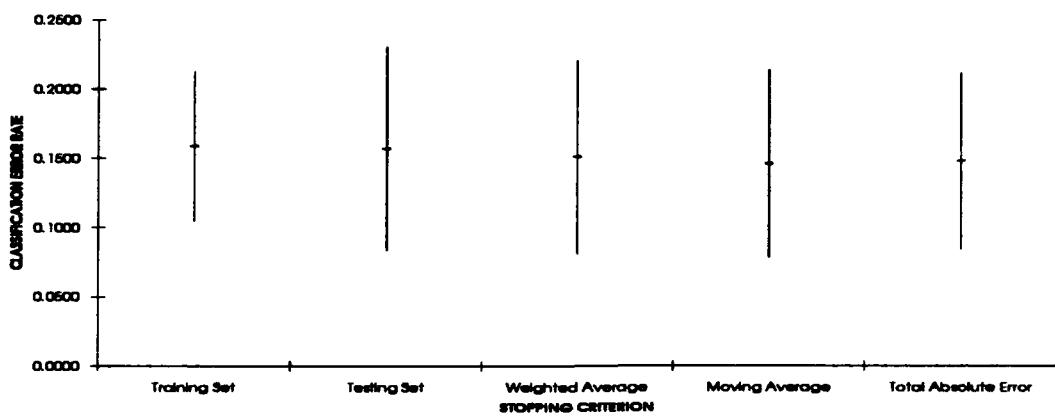


Figure 29. Mesh Classification Error Rate: Six Hidden Nodes

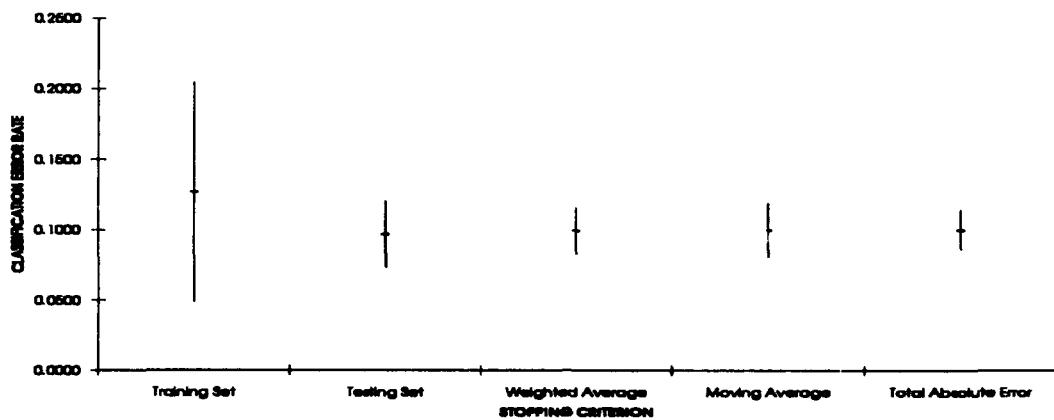


Figure 30. Mesh Classification Error Rate: Eight Hidden Nodes

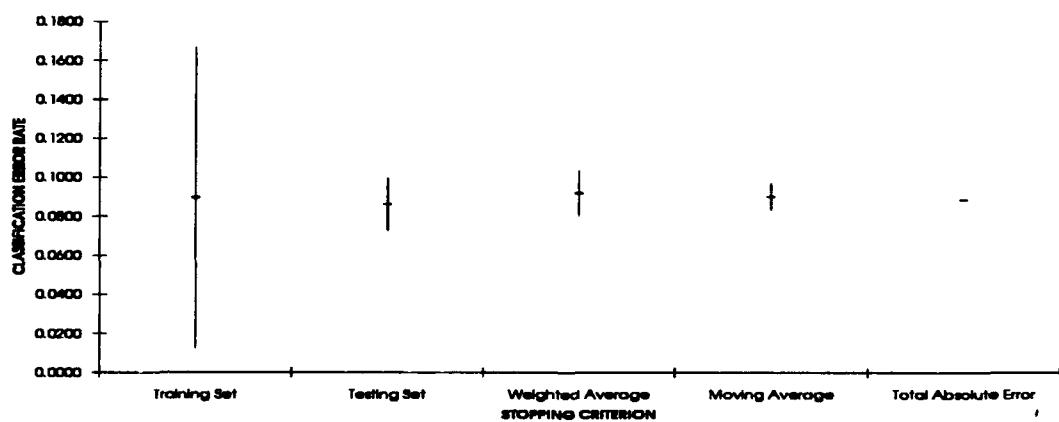


Figure 31. Mesh Classification Error Rate: Ten Hidden Nodes

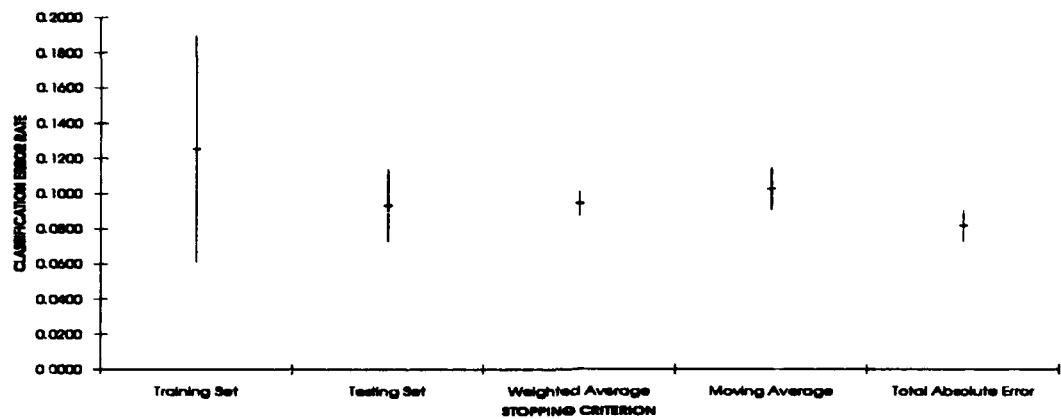


Figure 32. Mesh Classification Error Rate: Twelve Hidden Nodes

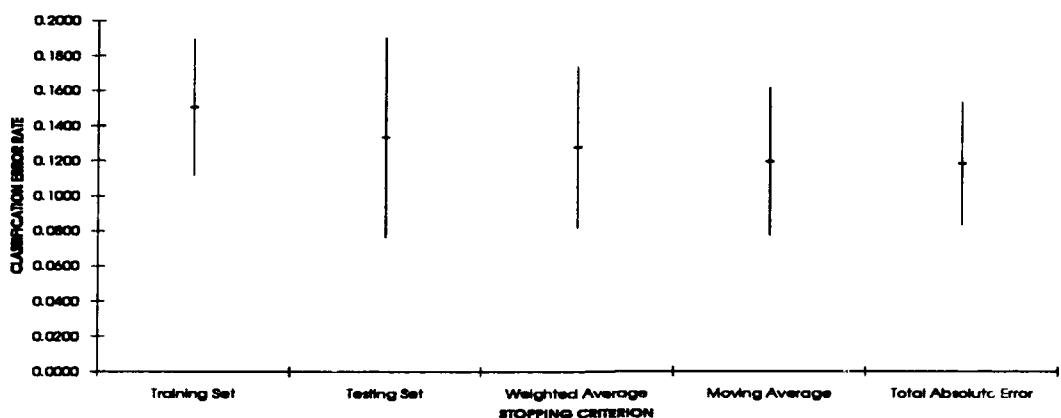


Figure 33. Mesh Classification Error Rate: Fourteen Hidden Nodes

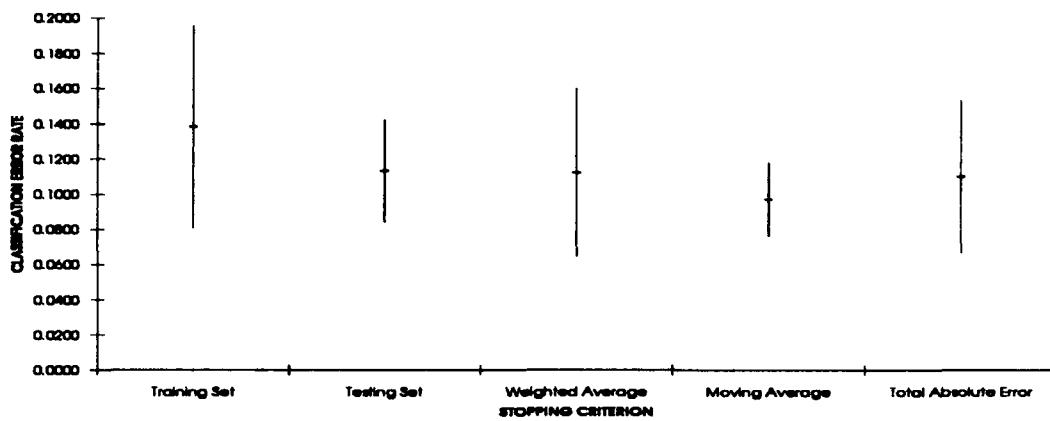


Figure 34. Mesh Classification Error Rate: Sixteen Hidden Nodes

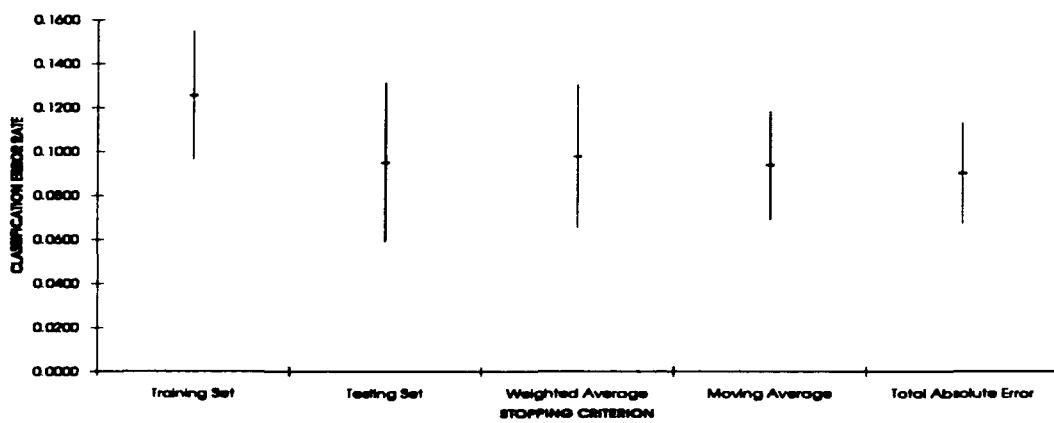


Figure 35. Mesh Classification Error Rate: Eighteen Hidden Nodes

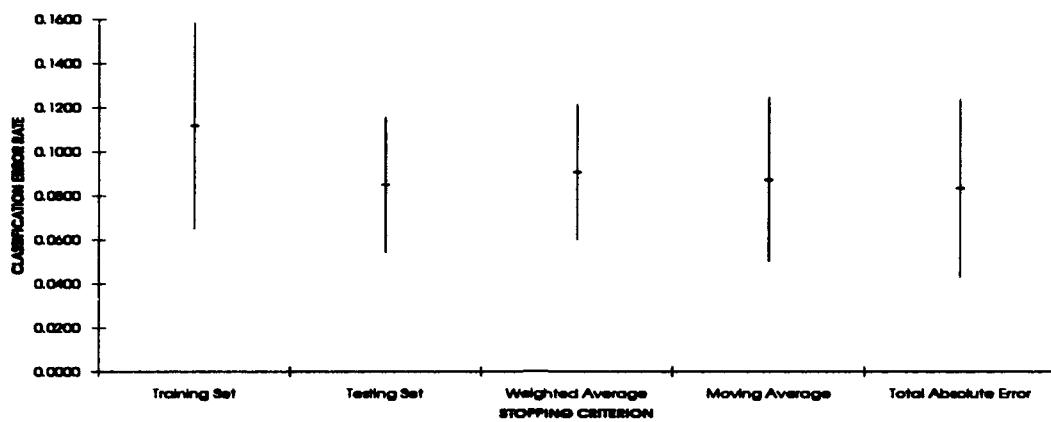


Figure 36. Mesh Classification Error Rate: Twenty Hidden Nodes

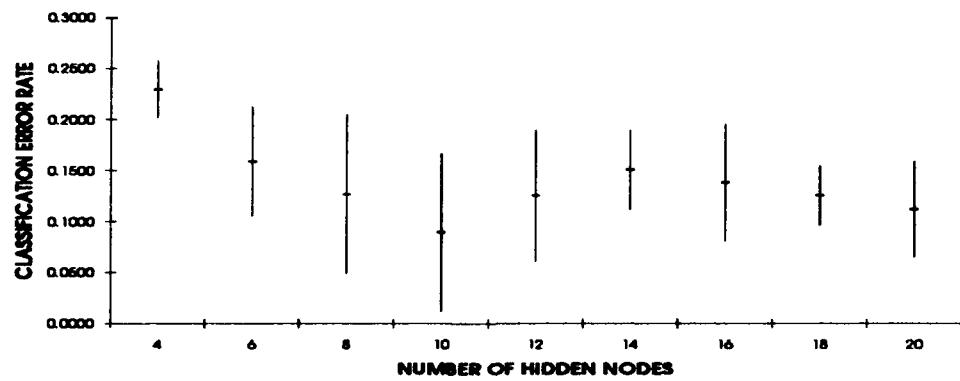


Figure 37. Mesh Problem: Training Set as Stopping Criterion

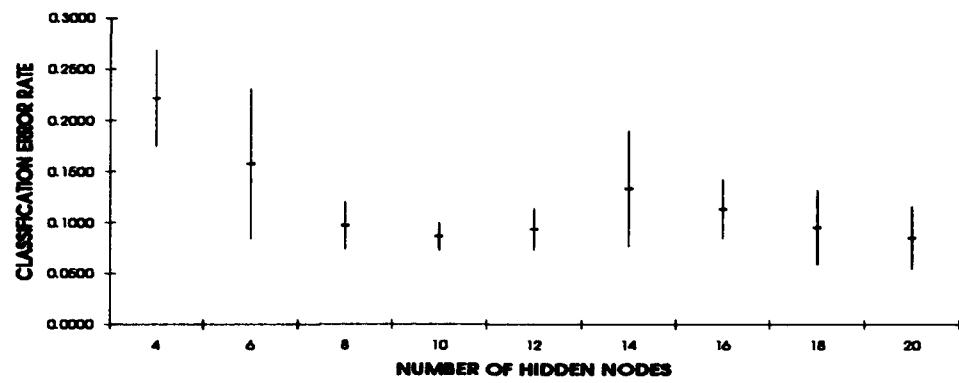


Figure 38. Mesh Problem: Testing Set as Stopping Criterion

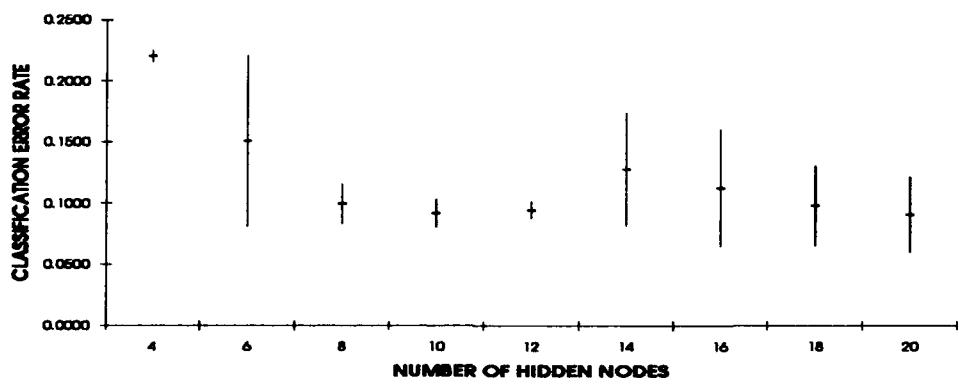


Figure 39. Mesh Problem: Weighted Average as Stopping Criterion

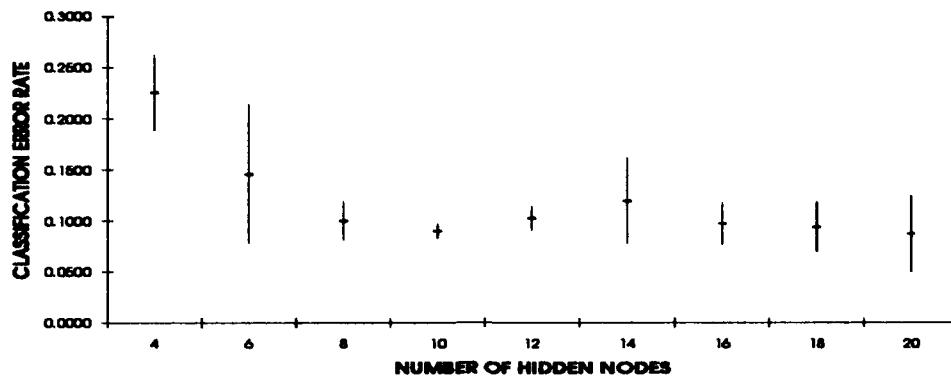


Figure 40. Mesh Problem: Moving Average as Stopping Criterion

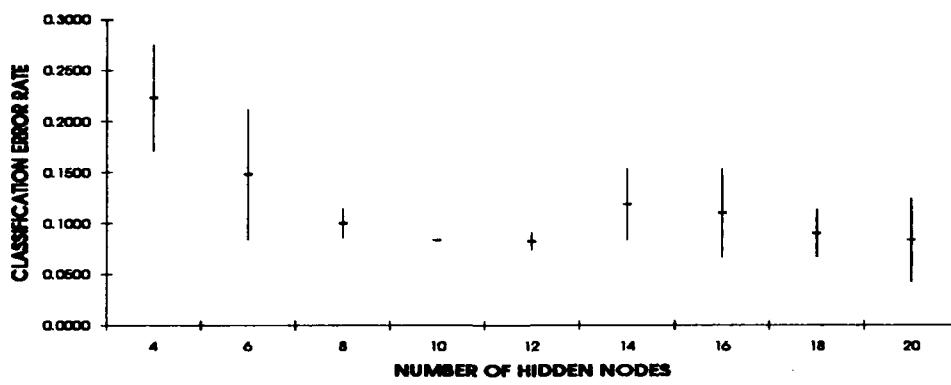


Figure 41. Mesh Problem: Total Absolute Error as Stopping Criterion

V. Results and Conclusions

5.1 A Successful Procedure

This study evaluated eleven characteristics of an artificial neural network (ANN) throughout training to determine the proper epoch at which to terminate ANN training. Based upon these characteristics, the following procedure resulted in selecting a final network which yielded a low classification error rate and also yielded a low classification error rate variance.

1. Perform at least ten replications of artificial neural network training using different random initial weights. Use the output of this sequence of experiments to determine when improvement or learning no longer occurs.
2. Perform artificial neural network training again using repeated cycles of an ANN with different random initial weights. Perform training only until the epoch at which learning no longer occurs as previously determined. Track the following functions as they occur in the testing set during this step: total absolute error, testing set classification error rate, and moving average of the testing set classification error rate.
3. Heuristically select those weights which perform well under the above three functions. Select a general grouping of the best of these, choosing at least two sets of weights for each stopping criterion. An acceptable ANN replication does well under all three categories. Generally, the area of the epoch and the initial weights will be acceptable across all three stopping criteria if the weights indicate the lowest level of classification error rate.
4. A random set of weights can then be selected from those weights designated as acceptable. Generally, this set of weights proved to yield a low classification error rate and a low variance of classification error rate. However, using this

procedure did not guarantee the lowest classification error rate on the validation set.

5.2 *Potential Future Research*

As with almost any area of research, progress leads toward more questions. The following extensions of this study are possible.

- Changing variables in the network to determine the impact. This study fixed a number of ANN attributes. If these were changed, the impact upon the conclusion is unknown. For example, the following could be changed: η (eta) or learning rate; the number of hidden layers; or values for the momentum term. Additionally, the interaction of these variables would seem to be of interest.
- Adding a momentum value. Since this study did not emphasize the speed at which a final ANN was determined, momentum was not in the ANN equation. The impact of adding it to the ANN equation is therefore unknown.
- Changing the maximum number of epochs. Early in the experiment process of this study, an assumption was made that ANN learning did not occur after epoch 600 for the particular network design of the XOR problem. However, the total absolute error on the testing set appeared to decrease slightly even after epoch 600. The impact of allowing the learning process to continue until the true minimum total absolute error is unknown. Particularly interesting would be the classification error rate at this final minimum.
- Using a variable momentum value. A variable momentum value is currently being researched and its impact upon the total absolute error is unknown.
- A more detailed study of overlearning. Two ANN techniques, the weighted average classification error rate and random exemplar assignment to either the training or the testing set, were designed to counteract the impact of the ten-

dency of ANN to overlearn. Since overlearning was not observed in this study, the usefulness of these tools is unknown. An examination of the techniques when overlearning occurs would be interesting.

5.2.1 Conclusion. This paper presented a technique which added insight for selecting the final ANN weights. It showed how looking at more than one function to analyze an ANN provided increased confidence that a given set of starting weights approached an optimal solution. Additionally, since a uniformly low classification error rate did not occur across all replications during ANN training, the study revealed the importance of using different initial weights and repeated replications of ANN training. In the final experiment, the number of hidden nodes was varied. This resulted in an example indicating that the ideal ANN structure (from eight to twelve hidden nodes for the mesh problem) exhibited a low classification error rate on the validation set and exhibited a low variance of that classification error rate. These respective low levels occurred for all three of the final stopping criteria judged best: classification error rate of the testing set, a moving average of the classification error rate on the testing set, and the total absolute error on the testing set. Finally, future extensions of the research for an improvement of this procedure were presented which show much room for future effort in the area of artificial neural networks.

Appendix A. FORTRAN Program

```
*****
* AS OF: 14 Feb 94
*
* The following program is a modified version of a program written
* by Lt Col Kenneth W. Bauer in April 1993. It uses the back
* propagation algorithm as documented by Lippmann and Rogers.
*
*****
*
* Variables in this program have the following meanings:
*
*   a:           temporary storage for sigmoid function value
*   abserrst:    level to stop training for total absolute error criterion
*   arrbig:      array of combined training and testing set
*   arrtng:      array of training set exemplars
*   arrtst:      array of testing set exemplars
*   arrval:      array of validation set exemplars
*   awcstop:     level to stop training for the absolute weight change
*                 criterion
*   ep:          epsilon, or the error. Lippmann's (d(j) - y(j)) term
*   errlrg:      level to stop training for the largest absolute error
*                 criterion
*   essstop1:    level to stop training for the error sum of squares
*                 criterion
*   errstop2:    level to stop training for the weighted average criterion
*   errsttng:    level to stop training for training set criterion
*   errsttst:    level to stop training for testing set criterion
*   errstval:    level to stop training for validation set criterion
*   eta:         gain term or step size
*   iaberr:      switch to have the program test for absolute error
*   icont1:      number of continuous epochs in which a characteristic
*                 must occur to trip a stopping criterion threshold
*   icount:      item number of the exemplar currently under evaluation
*   iepoch:      number of epochs conducted
*   interval:    length of interval for moving average computations
*   istop:       maximum number of iterations or epochs
*   itest:        switch to have the program test the test set
*   itrain:      switch to have the program test the training set
*   ival:        switch to have the program test the validation set
*   m:           number of inputs or features
*   mastop:     level to stop training for moving average criterion
*   mwcstop:    level to stop training for the mean absolute relative
*                 weight change criterion
```

```

*      n:      number of hidden units
*      ncstop:  number of ncycle before termination
*      ncycle:  number of times the complete program has run
*                  (with new weights for each iteration)
*      no:      number of output units
*      ntngpt:  number of data points in the training set (exemplars)
*      ntstpt:  number of data points in the testing set
*      nvalpt:  number of data points in the validation set
*      o:      number of output units = no
*      rwcstop: level to stop training for the absolute relative weight
*                  change criterion
*      sum:      Lippmann's delta(j) term for updating internal hidden mode
*                  weights
*      swcstop:  level to stop training for the squared weight change
*                  criterion
*      toterr:  total error for one exemplar and one epoch
*      w1:      layer 1 weights, i to j.  i = m+1 for the bias term
*      w2:      layer 2 weights, i to j.  i = n+1 for the bias term
*      xo:      input variables, to include bias term (1) and desired output
*      x1:      hidden layer outputs
*      xx:      array value used for mapping fort.10
*      zz:      computed value of hidden nodes.
*
*****
```

```
program ProgFin1
```

```
* Set neural net parameters and the size of the exemplar files
```

```
parameter(m=2,n=3,no=1,istop=500)
parameter(intervl=5)
parameter(icontl=2)
parameter(ncstop=2)
parameter(ntngpt=100)
parameter(ntstpt=100)
parameter(nvalpt=600)
```

```
***** if ioption = 0, then I am keeping the training and test sets separate
***** if ioption = 1, then I mix the training and test sets between epochs
```

```
parameter(ioption=0)
```

```
***** Parameters required for Shell-Mezgar sort routine
```

```
PARAMETER(ALN2I=1.0/0.69314718,TINY=1.0E-5)
```

```
* Initialize variables
```

```
real x0(m+3),x1(n+1),zz(no),ep(no)
real w1(m+1,n),w2(n+1,no)
real w1temp(m+1,n), w2temp(n+1,no)
```

```
real arrbig(m+3, 2*(ntngpt+ntstpt))
real arrtng(m+3,ntngpt), arrtst(m+2,ntstpt), arrval(m+2, nvalpt)
real mwcstop, mastop
integer xx(11,11)
integer o
real movavg(intervl), avg(intervl), rate(intervl)
```

***** Variables required for Shell-Mezgar sort routine

```
real rndm(ntngpt)
real rndm2(ntngpt+ntstpt)
```

* istXXX stands for i stop for reason XXX.

```
integer isttst(ncstop), isttrn(ncstop), istval(ncstop)
integer istcyc(ncstop), istwa(ncstop)
integer isttae(ncstop), isttaeb(ncstop), itemp1(ncstop)
integer istess(ncstop), istessb(ncstop), itemp2(ncstop)
integer istlae(ncstop), istlaeb(ncstop), itemp3(ncstop)
integer istawc(ncstop), istswc(ncstop), istrwc(ncstop)
integer istmwc(ncstop), istma(ncstop), isttrnb(ncstop)
integer itempa(ncstop), itempb(ncstop), itempc(ncstop)
integer itempd(ncstop), itempe(ncstop), itempf(ncstop)
integer itempg(ncstop)
integer isttstb(ncstop), istwab(ncstop), istrwcb(ncstop)
integer isttemp(ncstop)
```

* igrافXX is for graph switch number XX

```
integer igraf01(ncstop), igrat02(ncstop), igrat03(ncstop)
integer igrat04(ncstop), igrat05(ncstop), igrat06(ncstop)
integer igrat07(ncstop), igrat08(ncstop), igrat09(ncstop)
integer igrat10(ncstop), igrat11(ncstop), igrat12(ncstop)
integer igrat13(ncstop), igrat14(ncstop), igrat15(ncstop)
integer igrat16(ncstop), igrat17(ncstop), igrat18(ncstop)
integer igrat19(ncstop), igrat20(ncstop), igrat21(ncstop)
integer igrat22(ncstop), igrat23(ncstop), igrat24(ncstop)
integer igrat25(ncstop)
integer igrat31(ncstop), igrat32(ncstop), igrat33(ncstop)
integer igrat34(ncstop), igrat35(ncstop), igrat36(ncstop)
integer igrat37(ncstop), igrat38(ncstop), igrat39(ncstop)
```

* Set up the weighted average percentages

```
data pertrn/.50/
data pertst/.50/
data perval/0.0/
```

* Set gain term or step size in eta and the percent stopping criteria

```
data eta/.35/
```

```

* Set the parameters to force a stop of training at the following
* threshold levels

data errstng/1.0/
data errstst/1.0/
data errstval/1.0/
data errstop2/1.0/
data abserrst/4.0/
data essstop1/1.0/
data errlrg/.5/
data awcstop/.04/
data swcstop/.0003/
data rwcstop/.001/
data mwcstop/.004/
data mastop/.01/

***** Constants required for Shell-Mezgar sort routine

LOGNB2=INT(ALOG(FLOAT(ntngpt))*ALN2I+TINY)
LOGNB3=INT(ALOG(FLOAT(ntngpt+ntstpt))*ALN2I+TINY)

o=no

* iprint always = 1

iprint=1

* Switches for determining which set of data to test against

itest = 1
itrain = 1
ival = 1
iaberr = 1

* Initialize switches for determining reason program terminated

do 509 iii = 1, ncstop
  istcyc(iii) = 0
  isttst(iii) = 0
  isttrn(iii) = 0
  istval(iii) = 0
  istwa(iii) = 1
  istwab(iii) = 1
  isttae(iii) = 0
  isttaeb(iii) = 0
  itemp1(iii) = 0
  istess(iii) = 1
  istessb(iii) = 1
  itemp2(iii) = 0
  istlae(iii) = 0

```

```
istlaeb(iii) = 0
itemp3(iii) = 0
istawc(iii) = 1
istswc(iii) = 1
istrwc(iii) = 0
istrwcb(iii) = 0
istawc(iii) = 1
istma(iii) = 0
isttrnb(iii) = 0
isttstb(iii) = 0
itempa(iii) = 0
itempb(iii) = 0
itempc(iii) = 0
itempd(iii) = 0
itempe(iii) = 0
itempf(iii) = 0
itempg(iii) = 0
igraf01(iii) = 0
igraf02(iii) = 0
igraf03(iii) = 0
igraf04(iii) = 0
igraf05(iii) = 0
igraf06(iii) = 0
igraf07(iii) = 0
igraf08(iii) = 0
igraf09(iii) = 0
igraf10(iii) = 0
igraf11(iii) = 0
igraf12(iii) = 0
igraf13(iii) = 0
igraf14(iii) = 0
igraf15(iii) = 0
igraf16(iii) = 0
igraf17(iii) = 0
igraf18(iii) = 0
igraf19(iii) = 0
igraf20(iii) = 0
igraf21(iii) = 0
igraf22(iii) = 0
igraf23(iii) = 0
igraf24(iii) = 0
igraf25(iii) = 0
igraf31(iii) = 0
igraf32(iii) = 0
igraf33(iii) = 0
igraf34(iii) = 0
igraf35(iii) = 0
igraf36(iii) = 0
igraf37(iii) = 0
igraf38(iii) = 0
igraf39(iii) = 0
```

```

        isttemp(iii) = 0
509  continue

* read the exemplars into arrays
* THIS SECTION HAS TO CHANGE IF THERE ARE OTHER THAN FOUR COLUMNS.
* fort.22 contains the original training vectors
* fort.7 contains the original testing vectors
* fort.9 contains the original validation vectors

        do 21 iii = 1, ntngpt
            read(22,*) arrtng(1, iii), arrtng(2, iii),
*                  arrtng(3, iii), arrtng(4, iii)
21  continue

        do 22 iii = 1, ntstpt
            read(7,*) arrtst(1, iii), arrtst(2, iii),
*                  arrtst(3, iii), arrtst(4, iii)
22  continue

        do 23 iii = 1, nvalpt
            read(9,*) arrval(1, iii), arrval(2, iii),
*                  arrval(3, iii), arrval(4, iii)
23  continue

* read in the training and testing exemplars into one big array.

        rewind 22
        rewind 7

        do 24 iii = 1, ntngpt
            read(22,*) arrbig(1, iii), arrbig(2, iii),
*                  arrbig(3, iii), arrbig(4, iii)
            read(7,*) arrbig(1, ntngpt+iii), arrbig(2, ntngpt+iii),
*                  arrbig(3, ntngpt+iii), arrbig(4, ntngpt+iii)
24  continue

* Set ibdg = 1 to get a file of the audit trail of the program.

        ibdg=0

        write (*,*) '# inputs, # hidden units, # output units'
        write (*,*) m,n,no
        write (*,*) '# exemplars, # epochs'
        write (*,*) ntngpt,istop
        write (*,*) 'step size'
        write (*,*) eta
        if (ibdg.eq.1) then
            write (*,*) 'Debug writes in fort.2'
        endif
        write (*,*) 'Final weights and net predictions in fort.2'

```

```

write (*,*) 'Activation Map in fort.10'
write (*,*) 'Class Rate on Train Set in fort.11'
write (*,*) 'Class Rate on Test Set in fort.12'
write (*,*) 'Class Rate on Val Set in fort.13'
write (*,*) 'Tot Absolute Err on Test Set in fort.14'
write (*,*) 'Tot Err Sum of Squar on Test Set in fort.15'
write (*,*) 'Largest Absolute Error on Test Set in fort.16'
write (*,*) 'Weighted Average Error Rate in fort.17'
write (*,*) 'Moving average calculations in fort.18'
write (*,*) 'Absolute Weight Change in fort.41'
write (*,*) 'Squared Weight Change in fort.42'
write (*,*) 'Relative Weight Change in fort.43'
write (*,*) 'Mean Weight Change in fort.44'
write (*,*) 'Summary writes in fort.50'
write (*,*) 'Stopping points write in fort.60 and on'

write (2,*)(x0(k),k=1,m),x0(m+2),zz(1)
write (50,*) 'SUMMARY FILE'
write (50,*) 'EPOCH, ERR RATE ON VAL SET, REASON'
write (50,*) ' '
write (50,*) 'STARTING CYCLE NUMBER ', ncycle + 1
write (50,*) ' '

* Initialize the random number generator seed to any negative number

idum = (-1)
idum2 = (-2)
idum0 = (-3)

* Initialize the criteria for number of cycles to run

ncycle = 1

* Continue if there is not enough cycles to stop.

501 write (2,*) ' '
write (2,*) ' '
write (2,*) 'WEIGHTS FOR CYCLE NUMBER ', ncycle

continue

* randomly initialize the weights to include weights for the nodes and
* weights for the bias term. Bias term is the reason for m+1 and
* n+1 instead of m and n respectively.
* Use numwts to count the number of weights.

numwts = 0

do 100 i=1,m+1
  do 100 j=1,n
    w1(i,j)=rano(idum)

```

```

        w1temp(i,j) = w1(i,j)
        numwts = numwts + 1
100    continue
        do 101 i=1,n+1
        do 101 j=1,o
          w2(i,j)=rano(idum)
          w2temp(i,j) = w2(i,j)
          numwts = numwts + 1
101    continue

        iepoch=0
1      icount=0

* BEGIN LOOP TO RANDOMLY REORDER THE TRAINING EXEMPLARS

***** Randomly sort training vectors for input to network. RNDM is used to
***** hold random numbers. These random numbers are then paired with the
***** training vectors. A Shell-Mezgar sort is then performed using RNDM as
***** the sort key. This yields a random ordering of the training vectors.
***** THIS ROUTINE WAS CODED BY GREG REINHART.

        if (ioption.eq.1) then
          go to 9001
        else
          continue
        endif

        DO 1912 I=1,ntngpt
          RNDM(I)=RANO(RANDOM)
1912    CONTINUE
        Mgreg=ntngpt
        DO 1915 NN=1,LOGNB2
          Mgreg=Mgreg/2
          K=ntngpt-Mgreg
          DO 1913 J=1,K
            I=J
1917          L=I+Mgreg
          IF(RNDM(L).LT.RNDM(I)) THEN
            temp9=RNDM(I)
            RNDM(I)=RNDM(L)
            RNDM(L)=temp9
            DO 1920 MM=1,m+2
              temp9=arrtng(I,MM)
              arrtng(I,MM)=arrtng(L,MM)
              arrtng(L,MM)=temp9
1920          CONTINUE
            I=I-Mgreg
            IF(I.GE.1) GOTO 1917
          ENDIF
1913    CONTINUE
1915    CONTINUE

```

```

9001  continue

    if (ioption.eq.0) then
        go to 9002
    else
        continue
    endif

        DO 9912 I=1,ntngpt + ntstp
        RNDM2(I)=RANO(RANDOM)
9912    CONTINUE
        Mgreg=ntngpt+ntstp
        DO 9915 MM=1,LOGNB3
        Mgreg=Mgreg/2
        K=ntngpt+ntstp-Mgreg
        DO 9913 J=1,K
        I=J
9917    L=I+Mgreg
        IF(RNDM(L).LT.RNDM(I)) THEN
            temp9=RNDM(I)
            RNDM(I)=RNDM(L)
            RNDM(L)=temp9
            DO 9920 MM=1,m+2
                temp9=arrbig(I,MM)
                arrbig(I,MM)=arrbig(L,MM)
                arrbig(L,MM)=temp9
9920    CONTINUE
        I=I-Mgreg
        IF(I.GE.1) GOTO 9917
    ENDIF
9913    CONTINUE
9915    CONTINUE

9002  continue

* END LOOP TO REORDER TRAINING EXEMPLARS

    iepoch=iepoch+1

* iswitch tells if a stopping criterion has been met this epoch

    iswitch = 0

2    ictcount=ictcount+1

* debug loop
    if(idbg.eq.1)then
        write(2,*)"input data --- ictcount --- iepoch"
        write(2,*)(x0(i),i=1,m+2),ictcount,iepoch
    endif

```

```

        if (ioption.eq.1) then
            go to 9003
        else
            continue
        endif

* FEEDFORWARD: for each input node, compute an output on the first
* layer x1(ii) and an input to the hidden layer.
* use m+1 to include the bias term

        do 10 ii=1,n
            a=0.
            do 20 ll=1,m+1
20        a=a+w1(ll,ii)*arrtng(ll,icount)
10        x1(ii)=f(a)

* debug loop
        if(idbg.eq.1)then
            write(2,*)"Hidden Layer Outputs"
            write(2,*)x1
        endif

* set up bias term for hidden layer

        x1(n+1)=1.0

* continuation of feedforward loop. compute an output term zz(jj)

        do 30 jj=1,o
            a=0.
            do 40 ii=1,n+1
40        a=a+w2(ii,jj)*x1(ii)
30        zz(jj)=f(a)

* debug loop
        if(idbg.eq.1)then
            write(2,*)"Output Layer Outputs"
            write(2,*)zz
        endif

* COMPUTE ERROR. x0(m+2) is the input desired answer.

        do 50 jj=1,o
50        ep(jj)=arrtng(m+2,icount)-zz(jj)

* debug loop
        if(idbg.eq.1)then
            write(2,*)"LAYER 1 WEIGHTS ---- BEFORE UPDATES"
            do 300 i=1,m+1
300        write(2,131) (w1(i,j),j=1,n)

```

```

        write(2,*)'LAYER 2 WEIGHTS ---- BEFORE UPDATES'
        do 301 i=1,n+1
301      write(2,131)(w2(i,j),j=1,o)
        endif

131      format(1x,8f8.3)

*  OUTPUT LAYER WEIGHT UPDATE.
*  the term ep(jj)*(1.-zz(jj))*zz(jj) is Lippmann's delta(j) term

        x1(n+1)=1.0
        do 60 ii=1,n+1
        do 60 jj=1,o
60      w2(ii,jj)=w2(ii,jj)+ep(jj)*(1.-zz(jj))*zz(jj)*x1(ii)*eta

*  HIDDEN LAYER WEIGHT UPDATE.
*  the term ep(jj)*(1.-zz(jj))*zz(jj)*w2(ii,jj) is Lippmann's term delta(k),
*  with the sum part used to make a summation.
*  x0(ll) is Lippmann's term x-prime(i).
*  the term sum*(1.-x1(ii))*x1(ii) is Lippmann's term delta(j).

        do 80 ii=1,n
        do 80 ll=1,m+1
        sum=0.
        do 90 jj=1,o
90      sum=sum+ep(jj)*(1.-zz(jj))*zz(jj)*w2(ii,jj)
80      w1(ll,ii)=w1(ll,ii)+(1.-x1(ii))*x1(ii)*arrtng(ll,icount)*sum*eta

9003  continue

        if (ioption.eq.0) then
          go to 9004
        else
          continue
        endif

*  FEEDFORWARD: for each input node, compute an output on the first
*  layer x1(ii) and an input to the hidden layer.
*  use m+1 to include the bias term

        do 9010 ii=1,n
        a=0.
        do 9020 ll=1,m+1
9020      a=a+w1(ll,ii)*arrbig(ll,icount)
9010      x1(ii)=f(a)

* debug loop
        if(idbg.eq.1)then
          write(2,*)'Hidden Layer Outputs'
          write(2,*)x1
        endif

```

```

* set up bias term for hidden layer

x1(n+1)=1.0

* continuation of feedforward loop.  compute an output term zz(jj)

do 9030 jj=1,o
  a=0.
  do 9040 ii=1,n+1
9040    a=a+w2(ii,jj)*x1(ii)
9030    zz(jj)=f(a)

* debug loop
  if(idbg.eq.1)then
    write(2,*)'Output Layer Outputs'
    write(2,*)zz
  endif

* COMPUTE ERROR.  x0(m+2) is the input desired answer.

do 9050 jj=1,o
9050    ep(jj)=arrbig(m+2,icount)-zz(jj)

* debug loop
  if(idbg.eq.1)then
    write(2,*)'LAYER 1 WEIGHTS ---- BEFORE UPDATES'
    do 9300 i=1,m+1
9300      write(2,131) (w1(i,j),j=1,n)
    write(2,*)'LAYER 2 WEIGHTS ---- BEFORE UPDATES'
    do 9301 i=1,n+1
9301      write(2,131)(w2(i,j),j=1,o)
  endif

* OUTPUT LAYER WEIGHT UPDATE.
* the term ep(jj)*(1.-zz(jj))*zz(jj) is Lippmann's delta(j) term

x1(n+1)=1.0
do 9060 ii=1,n+1
  do 9060 jj=1,o
9060    w2(ii,jj)=w2(ii,jj)+ep(jj)*(1.-zz(jj))*zz(jj)*x1(ii)*eta

* HIDDEN LAYER WEIGHT UPDATE.
* the term ep(jj)*(1.-zz(jj))*zz(jj)*w2(ii,jj) is Lippmann's term delta(k),
* with the sum part used to make a summation.
* x0(ll) is Lippmann's term x^prime(i).
* the term sum*(1.-x1(ii))*x1(ii) is Lippmann's term delta(j).

do 9080 ii=1,n
  do 9080 ll=1,m+1
    sum=0.

```

```

        do 9090 jj=1,o
9090      sum=sum+ep(jj)*(1.-zz(jj))*zz(jj)*w2(ii,jj)
9080      w1(ll,ii)=w1(ll,ii)+(1.-x1(ii))*x1(ii)*arrbig(ll,icount)*sum*eta

9004  continue

* debug loop
  if(idbg.eq.1)then
    write(2,*)'LAYER 1 WEIGHTS ----- AFTER UPDATES'
    do 400 i=1,m+1
400      write(2,131) (w1(i,j),j=1,n)
    write(2,*)'LAYER 2 WEIGHTS ----- AFTER UPDATES'
    do 401 i=1,n+1
401      write(2,131)(w2(i,j),j=1,o)
    endif

* If all of the exemplars have been checked, continue and compute error.
* Otherwise, take the else path and return to 2
*           the else block is toward the end of the program.

      if(ntngpt.eq.icount)then

* If all exemplars have been checked, begin checking for stopping
*   criteria.

*****
*
*
* BEGIN STOPPING CRITERIA CALCULATIONS
*
*
*****



****      FIND CLASSIFICATION ERROR RATE FOR TRAINING SET
****

      if (ioption.eq.1) then
        go to 9005
      else
        continue
      endif

      if (itrain.eq.1) then
        nclas9 = 0
        do 1502 ii = 1, ntngpt

* FEEDFORWARD: for each input node, compute an output on the first
*   layer x1(ii) and an input to the hidden layer.
*   use m+1 to include the bias term

```

```

        do 1510 ii=1,n
          b=0.
          do 1520 ll=1,m+1
1520      b=b+w1(ll,ii)*arrtng(ll,ii)
1510      x1(ii)=f(b)

* debug loop
  if(idbg.eq.1)then
    write(2,*)"Hidden Layer Outputs"
    write(2,*)x1
  endif

* set up bias term for hidden layer

  x1(n+1)=1.0

* continuation of feedforward loop.  compute an output term zz(jj)

  do 1530 jj=1,o
    b=0.
    do 1540 ii=1,n+1
1540      b=b+w2(ii,jj)*x1(ii)
      zz(jj)=f(b)

* discretize the classification

  if (zz(jj).lt.(.5)) then
    iclass = 0
  else
    iclass = 1
  endif

1530      continue

* compare to desired result

  if (iclass.eq.nint(arrtng(m+2,ii))) then
    nclas9 = nclas9 + 1
  else
    continue
  endif

1502      continue

  clasrat1 = (real(nclas9))/(real(ntngpt))

  write(11,*) iepoch, 1.0 - clasrat1
  else
    continue
  endif

```

```

9005  continue

    if (ioption.eq.0) then
        go to 9005
    else
        continue
    endif

    if (itrain.eq.1) then
        nclas9 = 0
        do 9502 ii = 1, ntngpt

* FEEDFORWARD: for each input node, compute an output on the first
* layer x1(ii) and an input to the hidden layer.
* use m+1 to include the bias term

        do 9510 ii=1,n
            b=0.
            do 9520 ll=1,m+1
9520            b=b+w1(ll,ii)*arrbig(ll,ii)
9510            x1(ii)=f(b)

* debug loop
        if(idbg.eq.1)then
            write(2,*)"Hidden Layer Outputs"
            write(2,*)x1
        endif

* set up bias term for hidden layer

        x1(n+1)=1.0

* continuation of feedforward loop. compute an output term zz(jj)

        do 9530 jj=1,o
            b=0.
            do 9540 ii=1,n+1
9540            b=b+w2(ii,jj)*x1(ii)
            zz(jj)=f(b)

* discretize the classification

        if (zz(jj).lt.(.5)) then
            iclass = 0
        else
            iclass = 1
        endif

9530      continue

* compare to desired result

```

```

        if (iclass.eq.nint(arrbig(m+2,ii))) then
            nclas9 = nclas9 + 1
        else
            continue
        endif

9502    continue

        clasrat1 = (real(nclas9))/(real(ntngpt))

        write(11,*) iepoch, 1.0 - clasrat1
    else
        continue
    endif

9006    continue

****

**** END: FIND CLASSIFICATION ERROR RATE FOR TRAINING SET
****

****

**** FIND CLASSIFICATION ERROR RATE FOR TESTING SET
****

        if (ioption.eq.1) then
            go to 9007
        else
            continue
        endif

        if (itest.eq.1) then
            nclas3 = 0

            do 1503 ii = 1, ntstp
* FEEDFORWARD: for each input node, compute an output on the first
* layer x1(ii) and an input to the hidden layer.
* use m+1 to include the bias term

                do 1511 ii=1,n
                b=0.
                do 1521 ll=1,m+1
1521          b=b+w1(ll,ii)*arrtst(ll,ii)
1511          x1(ii)=f(b)

* debug loop
            if(idbg.eq.1)then
                write(2,*)"Hidden Layer Outputs"
                write(2,*)x1

```

```

        endif

* set up bias term for hidden layer

        x1(n+1)=1.0

* continuation of feedforward loop.  compute an output term zz(jj)

        do 1531 jj=1,o
          b=0.
          do 1541 ii=1,n+1
1541          b=b+w2(ii,jj)*x1(ii)
          zz(jj)=f(b)

* discretize the classification

          if (zz(jj).lt.(.5)) then
            iclass = 0
          else
            iclass = 1
          endif

1531      continue

* compare to desired result

          if (iclass.eq.nint(arrtst(m+2,i1))) then
            nclas3 = nclas3 + 1
          else
            continue
          endif

1503      continue

          clasrat2 = (real(nclas3))/(real(ntstpt))

          write(12,*) iepoch, 1.0 - clasrat2
        else
          continue
        endif

9007      continue

        if (ioption.eq.0) then
          go to 9008
        else
          continue
        endif

        if (itest.eq.1) then
          nclas3 = 0

```

```

do 9503 i1 = ntngpt+1, ntngpt+ntstatpt

* FEEDFORWARD: for each input node, compute an output on the first
* layer x1(ii) and an input to the hidden layer.
* use m+1 to include the bias term

do 9511 ii=1,n
  b=0.
  do 9521 ll=1,m+1
9521      b=b+w1(ll,ii)*arrbig(ll,ii)
9511      x1(ii)=f(b)

* debug loop
  if(idbg.eq.1)then
    write(2,*)"Hidden Layer Outputs"
    write(2,*)x1
  endif

* set up bias term for hidden layer

  x1(n+1)=1.0

* continuation of feedforward loop.  compute an output term zz(jj)

do 9531 jj=1,o
  b=0.
  do 9541 ii=1,n+1
9541      b=b+w2(ii,jj)*x1(ii)
      zz(jj)=f(b)

* discretize the classification

  if (zz(jj).lt.(.5)) then
    iclass = 0
  else
    iclass = 1
  endif

9531      continue

* compare to desired result

  if (iclass.eq.nint(arrbig(m+2,ii))) then
    nclas3 = nclas3 + 1
  else
    continue
  endif

9503      continue

```

```

        clasrat2 = (real(nclas3))/(real(ntstpt))

        write(12,*) iepoch, 1.0 - clasrat2
    else
        continue
    endif

9008 continue

**** BEGIN UPDATE OF MOVING AVERAGE OF LAST interval OBSERVATIONS

    if (iepoch.le.intervl) then
        avg(iepoch) = 1.0 - clasrat2
        temp5 = 0.0
        do 701 ij = 1, iepoch
            temp5 = temp5 + avg(ij)
701     continue
        movavg(iepoch) = temp5/(real(iepoch))
        rate(iepoch) = 1.0 - clasrat2
    else
        continue
    endif

    if (iepoch.gt.intervl) then
        temp6 = rate(1)
* update the rate block
        do 703 ij = 1, interv1
            rate(ij) = rate(ij + 1)
703     continue
        do 706 ij = 1, interv1
            movavg(ij) = movavg(ij + 1)
706     continue
        rate(intervl) = 1.0 - clasrat2
        movavg(intervl) = movavg(intervl - 1) + ((rate(intervl)
*           - temp6)/(real(intervl)))
        write (18,*) iepoch, movavg(intervl)
    else
        continue
    endif

**** END UPDATE OF MOVING AVERAGE OF LAST interval OBSERVATIONS

****

**** END: FIND CLASSIFICATION ERROR RATE FOR TESTING SET
****

****

**** FIND CLASSIFICATION ERROR RATE FOR VALIDATION SET

```

```

****

      if (ival.eq.1) then
        nclas2 = 0

        do 1504 i1 = 1, nvalpt

* FEEDFORWARD: for each input node, compute an output on the first
* layer x1(ii) and an input to the hidden layer.
* use m+1 to include the bias term

        do 1512 ii=1,n
          b=0.
          do 1522 ll=1,m+1
1522          b=b+w1(ll,ii)*arrval(ll,ii)
1512          x1(ii)=f(b)

* debug loop
  if(idbg.eq.1)then
    write(2,*)"Hidden Layer Outputs"
    write(2,*)x1
  endif

* set up bias term for hidden layer

  x1(n+1)=1.0

* continuation of feedforward loop. compute an output term zz(jj)

  do 1532 jj=1,o
    b=0.
    do 1542 ii=1,n+1
1542    b=b+w2(ii,jj)*x1(ii)
    zz(jj)=f(b)

* discretize the classification

    if (zz(jj).lt.(.5)) then
      iclass = 0
    else
      iclass = 1
    endif

1532    continue

* compare to desired result

  if (iclass.eq.nint(arrval(m+2,i1))) then
    nclas2 = nclas2 + 1
  else
    continue

```

```

        endif

1504      continue

      clasrat5 = (real(nclas2))/(real(nvalpt))

      write(13,*) iepoch, 1.0 - clasrat5
      else
        continue
      endif

*****
***** END: FIND CLASSIFICATION ERROR RATE FOR VALIDATION SET
***** 

*****
***** BEGIN COMPUTING TOTAL ABSOLUTE ERROR ON TESTING SET
***** THIS LOOP ALSO COMPUTES ERROR SUM OF SQUARES
***** THIS LOOP ALSO COMPUTES LARGEST ABSOLUTE ERROR
***** 

      if (iaberr.eq.1) then
        temp1 = 0.0
        temp2 = 0.0
        temp3 = 0.0

        do 1505 i1 = 1, ntstpt

* FEEDFORWARD: for each input node, compute an output on the first
* layer x1(ii) and an input to the hidden layer.
* use m+1 to include the bias term

        do 1513 ii=1,n
          b=0.
          do 1523 ll=1,m+1
1523          b=b+w1(ll,ii)*arrtst(ll,ii)
1513          x1(ii)=f(b)

* debug loop
          if(idbg.eq.1)then
            write(2,*)"Hidden Layer Outputs"
            write(2,*)x1
          endif

* set up bias term for hidden layer

          x1(n+1)=1.0

* continuation of feedforward loop. compute an output term zz(jj)

          do 1533 jj=1,o

```

```

b=0.
do 1543 ii=1,n+1
    b=b+w2(ii,jj)*x1(ii)
    zz(jj)=f(b)
    temp1 = temp1 + (abs(zz(jj) - nint(arrtst(m+2,i1))))
    temp2 = temp2 + (zz(jj) - nint(arrtst(m+2,i1)))**2
    if ((abs(zz(jj) - nint(arrtst(m+2,i1))))>.temp3) then
        temp3 = abs(zz(jj) - nint(arrtst(m+2,i1)))

* temp3a and temp3b track the coordinates of the exemplar
* causing the largest absolute error

        temp3a = arrtst(1,i1)
        temp3b = arrtst(2,i1)
        else
            continue
        endif

1533     continue

1505     continue

        write (14,*) iepoch, temp1
        write (15,*) iepoch, temp2
        write (16,*) iepoch, temp3, temp3a, temp3b
    else
        continue
    endif

****

**** END COMPUTING TOTAL ABSOLUTE ERROR ON TESTING SET
**** THIS LOOP ALSO COMPUTES ERROR SUM OF SQUARES
**** THIS LOOP ALSO COMPUTES LARGEST ABSOLUTE ERROR
****

****

**** BEGIN WEIGHT CHANGE CALCULATIONS
****

temp10 = 0.0
temp11 = 0.0
temp12 = 0.0
do 1100 i = 1, m + 1
    do 1101 j = 1, n
        temp10 = temp10 + abs(w1temp(i,j) - w1(i,j))
        temp11 = temp11 + (w1temp(i,j) - w1(i,j))**2
        temp12 = temp12 + abs((w1temp(i,j) - w1(i,j))/w1(i,j))
        w1temp(i,j) = w1(i,j)
1101     continue
1100     continue
    do 1102 i = 1, n + 1

```

```

        do 1103 j = 1, o
            temp10 = temp10 + abs(w2temp(i,j) - w2(i,j))
            temp11 = temp11 + (w2temp(i,j) - w2(i,j))**2
            temp12 = temp12 + abs((w2temp(i,j) - w2(i,j))/w1(i,j))
            w2temp(i,j) = w2(i,j)
1103      continue
1102      continue
        write (41,*) iepoch, temp10
        write (42,*) iepoch, temp11
        temp13 = temp12/numwts
        write (43,*) iepoch, temp13
        avgwts = temp10/numwts
        write (44,*) iepoch, avgwts

*****
**** END WEIGHT CHANGE CALCULATIONS
****

***** ****
*
*
* END STOPPING CRITERIA CALCULATIONS
*
*
***** ****

***** ****
*
*
* BEGIN CHECKING IF STOPPING CRITERIA HAVE BEEN MET
*
*
***** ****

* check for stopping criteria for limit on number of cycles reached

    if (istcyc(ncycle).eq.0) then
        if(iepoch.ge.istop) then
            write (2,*) ' '
            write (2,*) 'REASON FOR STOP IS NUMBER OF EPOCHS'
            write (2,*) 'IT IS EPOCH NUMBER ', iepoch
            write (2,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
            write (10,*) 'REASON FOR STOP IS NUMBER OF EPOCHS'
            write (10,*) 'IT IS EPOCH NUMBER ', iepoch
            write (10,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
            write (50,*) iepoch, 1.-clasrat5, ' MAX NUM EPOCHS'
            istcyc(ncycle) = istcyc(ncycle) + 1
            iswitch = iswitch + 1
        else
            continue
        endif

```

```

    else
        continue
    endif

* check for stopping criteria for low enough error rate on training set

    if (isttrn(ncycle).eq.0) then
        if(clasrat1.ge.errstng) then
            write (2,*) ''
            write (2,*) 'REASON FOR STOP IS ERROR RATE ON TRAINING SET'
            write (2,*) 'IT IS EPOCH NUMBER ', iepoch
            write (2,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
            write(10,*) 'REASON FOR STOP IS ERROR RATE ON TRAINING SET'
            write (10,*) 'IT IS EPOCH NUMBER ', iepoch
            write (10,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
            write (50,*) iepoch, 1.-clasrat5, ' ERR RATE ON TNG SET'
            isttrn(ncycle) = isttrn(ncycle) + 1
            iswitch = iswitch + 1
        else
            continue
        endif
    else
        continue
    endif

* check for stopping criteria for low enough error rate on training set
* occurring icont1 times in a row

    if (isttrnb(ncycle).eq.0) then

        if(clasrat1.ge.errstng) then
            itempa(ncycle) = itempa(ncycle) + 1
        else
            itempa(ncycle) = 0
        endif

        if (itempa(ncycle).ge.icont1) then
            write (2,*) ''
            write (2,*) 'REASON FOR STOP IS RPTD ERR RAT ON TNG SET'
            write (2,*) 'IT IS EPOCH NUMBER ', iepoch
            write (2,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
            write(10,*) 'REASON FOR STOP IS RPTD ERR RAT ON TNG SET'
            write (10,*) 'IT IS EPOCH NUMBER ', iepoch
            write (10,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
            write (50,*) iepoch, 1.-clasrat5, ' RPTD ER RAT TNG SET'
            isttrnb(ncycle) = isttrnb(ncycle) + 1
            iswitch = iswitch + 1
        else
            continue
        endif
    else

```

```

        continue
    endif

* check for stopping criteria for low enough error rate on testing set

    if (isttst(ncycle).eq.0) then
        if(clasrat2.ge.errsttst) then
            write (2,*) ''
            write (2,*) 'REASON FOR STOP IS ERROR RATE ON TESTING SET'
            write (2,*) 'IT IS EPOCH NUMBER ', iepoch
            write (2,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
            write(10,*) 'REASON FOR STOP IS ERROR RATE ON TESTING SET'
            write (10,*) 'IT IS EPOCH NUMBER ', iepoch
            write (10,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
            write (50,*) iepoch, 1.-clasrat5, ' ERR RATE ON TST SET'
            isttst(ncycle) = isttst(ncycle) + 1
            iswitch = iswitch + 1
        else
            continue
        endif
    else
        continue
    endif

* check for stopping criteria for low enough error rate on testing set
* occurring icont1 times in a row

    if (isttstb(ncycle).eq.0) then
        if(clasrat2.ge.errsttst) then
            itempb(ncycle) = itempb(ncycle) + 1
        else
            itempb(ncycle) = 0
        endif

        if (itempb(ncycle).ge.icont1) then
            write (2,*) ''
            write (2,*) 'REASON FOR STOP IS RPTD ERR RAT ON TST SET'
            write (2,*) 'IT IS EPOCH NUMBER ', iepoch
            write (2,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
            write(10,*) 'REASON FOR STOP IS RPTD ERR RAT ON TST SET'
            write (10,*) 'IT IS EPOCH NUMBER ', iepoch
            write (10,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
            write (50,*) iepoch, 1.-clasrat5, ' RPTD ER RAT TST SET'
            isttstb(ncycle) = isttstb(ncycle) + 1
            iswitch = iswitch + 1
        else
            continue
        endif
    else
        continue
    endif

```

```

        endif

* check for stopping criteria for low enough error rate on val set

if (istval(ncycle).eq.0) then
  if(clasrat5.ge.errstval) then
    write (2,*) ''
    write (2,*) 'REASON FOR STOP IS ERROR RATE ON VAL SET'
    write (2,*) 'IT IS EPOCH NUMBER ', iepoch
    write (2,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
    write(10,*) 'REASON FOR STOP IS ERROR RATE ON VAL SET'
    write (10,*) 'IT IS EPOCH NUMBER ', iepoch
    write (10,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
    write (50,*) iepoch, 1.-clasrat5, ' ERR RATE ON VAL SET'
    istval(ncycle) = istval(ncycle) + 1
    iswitch = iswitch + 1
  else
    continue
  endif
else
  continue
endif

* check for stopping criteria for low weighted average error rate

wtavg = pertrn*clasrat1 + pertst*clasrat2 + perval*clasrat5
write(17,*) iepoch, 1.0 - wtavg

if (istwa(ncycle).eq.0) then
  if(wtavg.ge.errstop2) then
    write (2,*) ''
    write (2,*) 'REASON FOR STOP IS WEIGHT AVE ERROR RATE'
    write (2,*) 'IT IS EPOCH NUMBER ', iepoch
    write (2,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
    write(10,*) 'REASON FOR STOP IS WEIGHT AVE ERROR RATE'
    write (10,*) 'IT IS EPOCH NUMBER ', iepoch
    write (10,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
    write (50,*) iepoch, 1.-clasrat5, ' WT AVG ERR RATE '
    istwa(ncycle) = istwa(ncycle) + 1
    iswitch = iswitch + 1
  else
    continue
  endif
else
  continue
endif

* check for stopping criteria for low weighted average error rate
* occurring icont1 times in a row

if (istwab(ncycle).eq.0) then

```

```

if(wtavg.ge.errstop2) then
    itempc(ncycle) = itempc(ncycle) + 1
else
    itempc(ncycle) = 0
endif

if (itempc(ncycle).ge.icont1) then
    write (2,*) ' '
    write (2,*) 'REASON FOR STOP IS RPTD WTD AVG ERROR RATE'
    write (2,*) 'IT IS EPOCH NUMBER ', iepoch
    write (2,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
    write(10,*) 'REASON FOR STOP IS RPTD WTD AVG ERROR RATE'
    write (10,*) 'IT IS EPOCH NUMBER ', iepoch
    write (10,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
    write (50,*) iepoch, 1.-clasrat5, ' RPTD WT AVG ERR RAT'
    istwab(ncycle) = istwab(ncycle) + 1
    iswitch = iswitch + 1
else
    continue
endif
else
    continue
endif

* check for stopping criteria for total absolute error

if (isttae(ncycle).eq.0) then
    if(temp1.le.abserrst) then
        write (2,*) ' '
        write (2,*) 'REASON FOR STOP IS TOTAL ABSOLUTE ERROR'
        write (2,*) 'IT IS EPOCH NUMBER ', iepoch
        write (2,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
        write(10,*) 'REASON FOR STOP IS TOTAL ABSOLUTE ERROR'
        write (10,*) 'IT IS EPOCH NUMBER ', iepoch
        write (10,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
        write (50,*) iepoch, 1.-clasrat5, ' TOT ABSOLUTE ERROR'
        isttae(ncycle) = isttae(ncycle) + 1
        iswitch = iswitch + 1
    else
        continue
    endif
else
    continue
endif

* check for stopping criteria for total absolute error
* occurring icont1 times in a row

if (isttaeb(ncycle).eq.0) then

```

```

if(temp1.le.abserrst) then
    itemp1(ncycle) = itemp1(ncycle) + 1
else
    itemp1(ncycle) = 0
endif

if (itemp1(ncycle).ge.icont1) then
    write (2,*) ''
    write (2,*) 'REASON FOR STOP IS REPEATED TOT ABS ERR'
    write (2,*) 'IT IS EPOCH NUMBER ', iepoch
    write (2,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
    write(10,*) 'REASON FOR STOP IS REPEATED TOT ABS ERR'
    write (10,*) 'IT IS EPOCH NUMBER ', iepoch
    write (10,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
    write (50,*) iepoch, 1.-clasrat5, ' RPTD TOT ABS ERROR'
    isttaeb(ncycle) = isttaeb(ncycle) + 1
    iswitch = iswitch + 1
else
    continue
endif
else
    continue
endif

* check for stopping criteria for error sum of squares

if (istess(ncycle).eq.0) then
    if(temp2.le.essstop1) then
        write (2,*) ''
        write (2,*) 'REASON FOR STOP IS ERROR SUM OF SQUARES'
        write (2,*) 'IT IS EPOCH NUMBER ', iepoch
        write (2,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
        write(10,*) 'REASON FOR STOP IS ERROR SUM OF SQUARES'
        write (10,*) 'IT IS EPOCH NUMBER ', iepoch
        write (10,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
        write (50,*) iepoch, 1.-clasrat5, ' ERR SUM OF SQUARES'
        istess(ncycle) = istess(ncycle) + 1
        iswitch = iswitch + 1
    else
        continue
    endif
else
    continue
endif

* check for stopping criteria for error sum of squares
* occurring icont1 times in a row

if (istessb(ncycle).eq.0) then

```

```

if(temp2.le.essstop1) then
    itemp2(ncycle) = itemp2(ncycle) + 1
else
    itemp2(ncycle) = 0
endif

if (itemp2(ncycle).ge.icont1) then
    write (2,*) ''
    write (2,*) 'REASON FOR STOP IS REPEATED ERR SUM SQ'
    write (2,*) 'IT IS EPOCH NUMBER ', iepoch
    write (2,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
    write(10,*) 'REASON FOR STOP IS REPEATED ERR SUM SQ'
    write (10,*) 'IT IS EPOCH NUMBER ', iepoch
    write (10,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
    write (50,*) iepoch, 1.-clasrat5, ' RPTD ERR SUM OF SQRS'
    istessb(ncycle) = istessb(ncycle) + 1
    iswitch = iswitch + 1
else
    continue
endif
else
    continue
endif

* check for stopping criteria for largest absolute error

if (istlae(ncycle).eq.0) then
    if(temp3.le.errlrg) then
        write (2,*) ''
        write (2,*) 'REASON FOR STOP IS LARGEST ABSOLT ERROR'
        write (2,*) 'IT IS EPOCH NUMBER ', iepoch
        write (2,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
        write(10,*) 'REASON FOR STOP IS LARGEST ABSOLT ERROR'
        write (10,*) 'IT IS EPOCH NUMBER ', iepoch
        write (10,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
        write (50,*) iepoch, 1.-clasrat5, ' LARGEST ABS ERROR'
        istlae(ncycle) = istlae(ncycle) + 1
        iswitch = iswitch + 1
    else
        continue
    endif
else
    continue
endif

* check for stopping criteria for largest absolute error
* occurring icont1 times in a row

if (istlaeb(ncycle).eq.0) then

    if(temp3.le.errlrg) then

```

```

        itemp3(ncycle) = itemp3(ncycle) + 1
else
        itemp3(ncycle) = 0
endif

if (itemp3(ncycle).ge.icont1) then
    write (2,*) ''
    write (2,*) 'REASON FOR STOP IS RPEATED LRG ABS ERR'
    write (2,*) 'IT IS EPOCH NUMBER ', iepoch
    write (2,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
    write(10,*) 'REASON FOR STOP IS RPEATED LRG ABS ERR'
    write (10,*) 'IT IS EPOCH NUMBER ', iepoch
    write (10,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
    write (50,*) iepoch, 1.-clasrat5, ' RPTD LARGE ABS ERROR'
    istlaeb(ncycle) = istlaeb(ncycle) + 1
    iswitch = iswitch + 1
else
    continue
endif
else
    continue
endif

* check for stopping criteria for absolute weight change

if (istawc(ncycle).eq.0) then
    if(temp10.le.awcstop) then
        write (2,*) ''
        write (2,*) 'REASON FOR STOP IS ABSOLUTE WEIGHT CHANGE'
        write (2,*) 'IT IS EPOCH NUMBER ', iepoch
        write (2,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
        write(10,*) 'REASON FOR STOP IS ABSOLUTE WEIGHT CHANGE'
        write (10,*) 'IT IS EPOCH NUMBER ', iepoch
        write (10,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
        write (50,*) iepoch, 1.-clasrat5, ' ABSOLUTE WEIGHT CHG'
        istawc(ncycle) = istawc(ncycle) + 1
        iswitch = iswitch + 1
    else
        continue
    endif
else
    continue
endif

* check for stopping criteria for squared weight change

if (istswc(ncycle).eq.0) then
    if(temp11.le.swcstop) then
        write (2,*) ''
        write (2,*) 'REASON FOR STOP IS SQUARED WEIGHT CHANGE'
        write (2,*) 'IT IS EPOCH NUMBER ', iepoch

```

```

        write (2,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
        write(10,*) 'REASON FOR STOP IS SQUARED WEIGHT CHANGE'
        write (10,*) 'IT IS EPOCH NUMBER ', iepoch
        write (10,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
        write (50,*) iepoch, 1.-clasrat5, ' SQUARED WEIGHT CHG'
        istawc(ncycle) = istawc(ncycle) + 1
        iswitch = iswitch + 1
    else
        continue
    endif
    else
        continue
    endif

* check for stopping criteria for absolute relative weight change

    if (istrwc(ncycle).eq.0) then
        if(temp13.le.rwcstop) then
            write (2,*) ''
            write (2,*) 'REASON FOR STOP IS RELATIVE WEIGHT CHANGE'
            write (2,*) 'IT IS EPOCH NUMBER ', iepoch
            write (2,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
            write(10,*) 'REASON FOR STOP IS RELATIVE WEIGHT CHANGE'
            write (10,*) 'IT IS EPOCH NUMBER ', iepoch
            write (10,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
            write (50,*) iepoch, 1.-clasrat5, ' RELATIVE WEIGHT CHG'
            istrwc(ncycle) = istrwc(ncycle) + 1
            iswitch = iswitch + 1
        else
            continue
        endif
    else
        continue
    endif

* check for stopping criteria for absolute relative weight change
* occurring icont1 times in a row

    if (istrwcb(ncycle).eq.0) then
        if(temp13.le.rwcstop) then
            itempf(ncycle) = itempf(ncycle) + 1
        else
            itempf(ncycle) = 0
        endif

        if (itempf(ncycle).ge.icont1) then
            write (2,*) ''
            write (2,*) 'REASON FOR STOP IS REPEATED REL WT CHG'
            write (2,*) 'IT IS EPOCH NUMBER ', iepoch
            write (2,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5

```

```

        write(10,*) 'REASON FOR STOP IS REPEATED REL WT CHG'
        write (10,*) 'IT IS EPOCH NUMBER ', iepoch
        write (10,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
        write (50,*) iepoch, 1.-clasrat5, ' RPTD REL WT CHG'
        istrwcb(ncycle) = istrwcb(ncycle) + 1
        iswitch = iswitch + 1
    else
        continue
    endif
else
    continue
endif

* check for stopping criteria for absolute mean weight change

if (istmwc(ncycle).eq.0) then
    if(avgnts.le.mwcstop) then
        write (2,*) ''
        write (2,*) 'REASON FOR STOP IS MEAN WEIGHT CHANGE'
        write (2,*) 'IT IS EPOCH NUMBER ', iepoch
        write (2,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
        write(10,*) 'REASON FOR STOP IS MEAN WEIGHT CHANGE'
        write (10,*) 'IT IS EPOCH NUMBER ', iepoch
        write (10,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
        write (50,*) iepoch, 1.-clasrat5, ' MEAN WEIGHT CHG'
        istmwc(ncycle) = istmwc(ncycle) + 1
        iswitch = iswitch + 1
    else
        continue
    endif
else
    continue
endif

* check for stopping criteria for moving average error
* need more than five epochs

if (iepoch.gt.5) then

    if (istma(ncycle).eq.0) then
        if(movavg(intervl).le.mastop) then
            write (2,*) ''
            write (2,*) 'REASON FOR STOP IS MOVING AVERAGE ERROR'
            write (2,*) 'IT IS EPOCH NUMBER ', iepoch
            write (2,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
            write(10,*) 'REASON FOR STOP IS MOVING AVERAGE ERROR'
            write (10,*) 'IT IS EPOCH NUMBER ', iepoch
            write (10,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
            write (50,*) iepoch, 1.-clasrat5, ' MOVING AVG ERROR'
            istma(ncycle) = istma(ncycle) + 1
            iswitch = iswitch + 1

```

```

        else
            continue
        endif
    else
        continue
    endif

    else
        continue
    endif

* BEGIN A MAP FOR EACH 50 EPOCHS

    if ( (iepoch.eq.50).or.(iepoch.eq.100).or.(iepoch.eq.150)
*   .or.
*   (iepoch.eq.200).or.(iepoch.eq.250).or.(iepoch.eq.300)
*   .or.
*   (iepoch.eq.350).or.(iepoch.eq.400).or.(iepoch.eq.450)
*   .or. (iepoch.eq.500) ) then

        write (2,*) ''
        write (2,*) 'PERIODIC EPOCH REPORT'
        write (2,*) 'IT IS EPOCH NUMBER ', iepoch
        write (2,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
        write(10,*) 'PERIODIC EPOCH REPORT'
        write (10,*) 'IT IS EPOCH NUMBER ', iepoch
        write (10,*) 'ERROR RATE ON VAL SET IS ', 1.0 - clasrat5
        write (50,*) iepoch, 1.-clasrat5, ' PERIOD EPOCH REPORT'
        iswitch = iswitch + 1

    else
        continue
    endif

*****
*
*
* BEGIN TEST FOR GRAPH DATA FOR TOTAL ABSOLUTE ERROR
* This section runs at the end of each epoch to determine if a
* threshold has been crossed. Initialize igrafXX at the
* beginning of the program and write to file fort.XX
* the first time the threshold is met
* Use igrafXX(ncycle) as a switch to see if this threshold
* has been met before
* Write to files number 61 and higher
* temp1 is the total absolute error value
*
*
*****
if (igraf01(ncycle).eq.0) then

```

```

        if (temp1.le.(1.0)) then
            write(61,*) ncycle, iepoch, 1.0 - clasrat5
            igrat01(ncycle) = igrat01(ncycle) + 1
        else
            continue
        endif
    else
        continue
    endif

    if (igrat02(ncycle).eq.0) then
        if (temp1.le.(2.0)) then
            write(62,*) ncycle, iepoch, 1.0 - clasrat5
            igrat02(ncycle) = igrat02(ncycle) + 1
        else
            continue
        endif
    else
        continue
    endif

*****
*
*
*  END TEST FOR GRAPH DATA FOR TOTAL ABSOLUTE ERROR
*
*
*****
*  iswitch is greater than 0 if a tolerance threshold had been met.

        if (iswitch.gt.0) then
            go to 3
        else
            continue
        endif

*****
*
*
*  END CHECKING IF STOPPING CRITERIA HAVE BEEN MET
*
*
*****
*  Take the go to 1 loop if program doesn't go to 3 above

        go to 1

* take else route if the entire training set isn't complete this epoch.
* This goes far back into the program to label 99.

```

```

    else
        go to 2
    endif

* When an iswitch value indicates that one of the potential stopping
* criterion has indicated a stopping point or a periodic activation
* map is desired, enter here to print out results to fort.2 and fort.10

3    if(iprint.eq.1)then

    rewind 30

    x0(3) = 1.0

    do 5000 i=11,1,-1
        do 5000 j=1,11

            read(30,*) x0(1), x0(2)

C FEEDFORWARD

    do 210 ii=1,n
        a=0.
        do 220 ll=1,m+1
220        a=a+w1(ll,ii)*x0(ll)
210        x1(ii)=f(a)

        x1(n+1)=1.0
        do 230 jj=1,o
            a=0.
            do 240 ii=1,n+1
240            a=a+w2(ii,jj)*x1(ii)
230            zz(jj)=f(a)
            xx(i,j)=ifix(100.*zz(1))
5000    continue

* Write to the activation map in fort.10

    write (10,*) ' '
    write (10,*) 'ACTIVATION MAP FOR CYCLE NUMBER ', ncycle
    write (10,*) ' '

    do 5001 i=11,1,-1
        write(10,1111)(xx(i,j),j=1,11)
1111    format(11(1x,i3))
5001    continue

    write (10,*) ' '
    write (10,*) ' '

```

```

* Write final weights to file fort.2

      write(2,*)'FINAL LAYER 1 WEIGHTS '
      do 410 i=1,m+1
410      write(2,131) (w1(i,j),j=1,n)
      write(2,*)'FINAL LAYER 2 WEIGHTS'
      do 411 i=1,n+1
411      write(2,131)(w2(i,j),j=1,o)

      endif

*****
*
* Determine if all of the possible stopping criteria have indicated
* that it is time to quit this cycle.
*
*****
*****
```

```

      if ((istcyc(ncycle).eq.1).and.(isttrn(ncycle).eq.1)
*      .and.(isttst(ncycle).eq.1).and.(istval(ncycle).eq.1)
*      .and.(istwa(ncycle).eq.1).and.(isttae(ncycle).eq.1)
*      .and.(isttaeb(ncycle).eq.1).and.(istess(ncycle).eq.1)
*      .and.(istessb(ncycle).eq.1).and.(istlae(ncycle).eq.1)
*      .and.(istlaeb(ncycle).eq.1)) then
         goto 507
      else
         if (istcyc(ncycle).eq.1) then
            if (isttrn(ncycle).eq.0) then
               write (2,*) ''
               write (2,*) 'TRAIN SET NOT MEET ERR CRIT IN EPOCHS'
               write (10,*) ''
               write (10,*) 'TRAIN SET NOT MEET ERR CRIT IN EPOCHS'
            else
               continue
            endif
         endif

         if (istcyc(ncycle).eq.1) then
            if (isttrnb(ncycle).eq.0) then
               write (2,*) ''
               write (2,*) 'RPTD TRN SET NOT MEET ERR CRIT IN EPOCHS'
               write (10,*) ''
               write (10,*) 'RPTD TRN SET NOT MEET ERR CRIT IN EPCHS'
            else
               continue
            endif
         endif

         if (istcyc(ncycle).eq.1) then
            if (isttst(ncycle).eq.0) then
               write (2,*) ''
```

```

        write (2,*) 'TEST SET NOT MEET ERR CRIT IN EPOCHS'
        write (10,*) ''
        write (10,*) 'TEST SET NOT MEET ERR CRIT IN EPOCHS'
    else
        continue
    endif
endif

if (istcyc(ncycle).eq.1) then
    if (isttstb(ncycle).eq.0) then
        write (2,*) ''
        write (2,*) 'RPTD TST SET NOT MEET ERR CRIT IN EPOCHS'
        write (10,*) ''
        write (10,*) 'RPTD TST SET NOT MEET ERR CRIT IN EPOCHS'
    else
        continue
    endif
endif

if (istcyc(ncycle).eq.1) then
    if (istval(ncycle).eq.0) then
        write (2,*) ''
        write (2,*) 'VAL SET NOT MEET ERR CRIT IN EPOCHS'
        write (10,*) ''
        write (10,*) 'VAL SET NOT MEET ERR CRIT IN EPOCHS'
    else
        continue
    endif
endif

if (istcyc(ncycle).eq.1) then
    if (istwa(ncycle).eq.0) then
        write (2,*) ''
        write (2,*) 'WEIGHT AVE NOT MEET ERR CRIT IN EPOCHS'
        write (10,*) ''
        write (10,*) 'WEIGHT AVE NOT MEET ERR CRIT IN EPOCHS'
    else
        continue
    endif
endif

if (istcyc(ncycle).eq.1) then
    if (istwab(ncycle).eq.0) then
        write (2,*) ''
        write (2,*) 'RPTD WT AVG NOT MEET ERR CRIT IN EPOCHS'
        write (10,*) ''
        write (10,*) 'RPT WT AVG NOT MEET ERR CRIT IN EPOCHS'
    else
        continue
    endif
endif

```

```

        endif

        if (istcyc(ncycle).eq.1) then
            if (isttae(ncycle).eq.0) then
                write (2,*) ''
                write (2,*) 'TOT ABS ERR NOT MEET ERR CRIT IN EPOCHS'
                write (10,*) ''
                write (10,*) 'TOT ABS ERR NOT MEET ERR CRIT IN EPCHS'
            else
                continue
            endif
        endif

        if (istcyc(ncycle).eq.1) then
            if (isttaeb(ncycle).eq.0) then
                write (2,*) ''
                write (2,*) 'RPTED TOT ABS ERR NOT MET ER CRT IN EP'
                write (10,*) ''
                write (10,*) 'RPTED TOT ABS ERR NOT MET ER CRT IN EP'
            else
                continue
            endif
        endif

        if (istcyc(ncycle).eq.1) then
            if (istess(ncycle).eq.0) then
                write (2,*) ''
                write (2,*) 'ERR SUM SQ NOT MEET ERR CRIT IN EPOCHS'
                write (10,*) ''
                write (10,*) 'ERR SUM SQ NOT MEET ERR CRIT IN EPCHS'
            else
                continue
            endif
        endif

        if (istcyc(ncycle).eq.1) then
            if (istessb(ncycle).eq.0) then
                write (2,*) ''
                write (2,*) 'RPTED ERR SUM SQ NOT MET ER CRT IN EP'
                write (10,*) ''
                write (10,*) 'RPTED ERR SUM SQ NOT MET ER CRT IN EP'
            else
                continue
            endif
        endif

        if (istcyc(ncycle).eq.1) then
            if (istlae(ncycle).eq.0) then
                write (2,*) ''
                write (2,*) 'LRG ABS ER NOT MEET ERR CRIT IN EPOCHS'
                write (10,*) ''

```

```

        write (10,*) 'LRG ABS ER NOT MEET ERR CRIT IN EPCHS'
        else
            continue
        endif
    endif

    if (istcyc(ncycle).eq.1) then
        if (istlaeb(ncycle).eq.0) then
            write (2,*) ''
            write (2,*) 'RPTED LRG ABS ER NOT MET ER CRT IN EP'
            write (10,*) ''
            write (10,*) 'RPTED LRG ABS ER NOT MET ER CRT IN EP'
        else
            continue
        endif
    endif

    if (istcyc(ncycle).eq.1) then
        if (istawc(ncycle).eq.0) then
            write (2,*) ''
            write (2,*) 'ABS WGHT CHANGE NOT MET ER CRT IN EP'
            write (10,*) ''
            write (10,*) 'ABS WGHT CHANGE NOT MET ER CRT IN EP'
        else
            continue
        endif
    endif

    if (istcyc(ncycle).eq.1) then
        if (istswc(ncycle).eq.0) then
            write (2,*) ''
            write (2,*) 'SQR WGHT CHANGE NOT MET ER CRT IN EP'
            write (10,*) ''
            write (10,*) 'SQR WGHT CHANGE NOT MET ER CRT IN EP'
        else
            continue
        endif
    endif

    if (istcyc(ncycle).eq.1) then
        if (istrwc(ncycle).eq.0) then
            write (2,*) ''
            write (2,*) 'REL WGHT CHANGE NOT MET ER CRT IN EP'
            write (10,*) ''
            write (10,*) 'REL WGHT CHANGE NOT MET ER CRT IN EP'
        else
            continue
        endif
    endif

    if (istcyc(ncycle).eq.1) then

```

```

if (istrwcb(ncycle).eq.0) then
  write (2,*) ''
  write (2,*) 'RPTD REL WT CHG NOT MET ER CRT IN EP'
  write (10,*) ''
  write (10,*) 'RPTD REL WT CHG NOT MET ER CRT IN EP'
else
  continue
endif
endif

if (istcyc(ncycle).eq.1) then
  if (istmwc(ncycle).eq.0) then
    write (2,*) ''
    write (2,*) 'MEAN WGHT CHANGE NOT MET ER CRT IN EP'
    write (10,*) ''
    write (10,*) 'MEAN WGHT CHANGE NOT MET ER CRT IN EP'
  else
    continue
  endif
endif

if (istcyc(ncycle).eq.1) then
  if (istma(ncycle).eq.0) then
    write (2,*) ''
    write (2,*) 'MOVING AVG ERROR NOT MET ER CRT IN EP'
    write (10,*) ''
    write (10,*) 'MOVING AVG ERROR NOT MET ER CRT IN EP'
  else
    continue
  endif
endif

if (istcyc(ncycle).eq.1) then
  goto 507
else
  continue
endif

goto 1
endif

* Update the number of cycles

507      ncycle = ncycle + 1
        write (50,*) ''
        write (50,*) 'STARTING CYCLE NUMBER ', ncycle
        write (50,*) ''

* Determine if there are a sufficient number of cycles.

        if (ncycle.le.ncstop) then

```

```

        goto 501
else
    continue
endif

stop
end

real function f(x)
f=1./(1.+exp(-1.*x))
return
end

*****
* RANDOM NUMBER GENERATOR
*
* Returns a uniform random deviate between 0.0 and 1.0 using a system
* Set IDUM to any negative value to initialize or reinitialize the sequence.
*
* Reference: Numerical Recipes, p. 196
*
*****
FUNCTION RAN1(IDUM)

DIMENSION R(97)
PARAMETER (M1=259200,IA1=7141,IC1=54773,RM1=1./M1)
PARAMETER (M2=134456,IA2=8121,IC2=28411,RM2=1./M2)
PARAMETER (M3=243000,IA3=4561,IC3=51349)
DATA IFF /0/
IF (IDUM.LT.0.OR.IFF.EQ.0) THEN
    IFF=1
    IX1=MOD(IC1-IDUM,M1)
    IX1=MOD(IA1*IX1+IC1,M1)
    IX2=MOD(IX1,M2)
    IX1=MOD(IA1*IX1+IC1,M1)
    IX3=MOD(IX1,M3)
    DO 11 J=1,97
        IX1=MOD(IA1*IX1+IC1,M1)
        IX2=MOD(IA2*IX2+IC2,M2)
        R(J)=(FLOAT(IX1)+FLOAT(IX2)*RM2)*RM1
11    CONTINUE
    IDUM=1
ENDIF
IX1=MOD(IA1*IX1+IC1,M1)
IX2=MOD(IA2*IX2+IC2,M2)
IX3=MOD(IA3*IX3+IC3,M3)
J=1+(97*IX3)/M3
IF(J.GT.97.OR.J.LT.1)PAUSE
RAN1=R(J)
R(J)=(FLOAT(IX1)+FLOAT(IX2)*RM2)*RM1

```

```

        RETURN
        END

*****
*  RANDOM NUMBER GENERATOR
*
*  Returns a uniform random deviate between 0.0 and 1.0 using a system
*  Set IDUM2 to any negative value to initialize or reinitialize the sequence.
*
*  Reference:  Numerical Recipes, p. 196
*
*****

FUNCTION RAN2(IDUM2)

DIMENSION R(97)
PARAMETER (M1=259200,IA1=7141,IC1=54773,RM1=1./M1)
PARAMETER (M2=134456,IA2=8121,IC2=28411,RM2=1./M2)
PARAMETER (M3=243000,IA3=4561,IC3=51349)
DATA IFF /0/
IF (IDUM2.LT.0.OR.IFF.EQ.0) THEN
  IFF=1
  IX1=MOD(IC1-IDUM2,M1)
  IX1=MOD(IA1*IX1+IC1,M1)
  IX2=MOD(IX1,M2)
  IX1=MOD(IA1*IX1+IC1,M1)
  IX3=MOD(IX1,M3)
  DO 11 J=1,97
    IX1=MOD(IA1*IX1+IC1,M1)
    IX2=MOD(IA2*IX2+IC2,M2)
    R(J)=(FLOAT(IX1)+FLOAT(IX2)*RM2)*RM1
11  CONTINUE
  IDUM2=1
ENDIF
IX1=MOD(IA1*IX1+IC1,M1)
IX2=MOD(IA2*IX2+IC2,M2)
IX3=MOD(IA3*IX3+IC3,M3)
J=1+(97*IX3)/M3
IF(J.GT.97.OR.J.LT.1)PAUSE
RAN2=R(J)
R(J)=(FLOAT(IX1)+FLOAT(IX2)*RM2)*RM1
RETURN
END

*****
*  RANDOM NUMBER GENERATOR.  RANO
*
*  Written by Lisa Belue.
*
*  Returns a uniform random deviate between 0.0 and 1.0 using a system
*  supplied routine RAN(ISEED).  Set IDUM to any negative value to

```

```

* initialize or reinitialize the sequence.
*
*****  

FUNCTION RANO(IDUM0)

DIMENSION V(97)
DATA IFF /0/
IF (IDUM.LT.0.OR.IFF.EQ.0) THEN
  IFF=1
  ISEED=ABS(IDUM)
  IDUM=1
  DO 11 J=1,97
    DUM=RAN(ISEED)
11  CONTINUE
  DO 12 J=1,97
    V(J)=RAN(ISEED)
12  CONTINUE
  Y=RAN(ISEED)
ENDIF
J=1+INT(97.*Y)
IF(J.GT.97.OR.J.LT.1) then
  PAUSE
else
  continue
endif
Y=V(J)
RANO=Y
V(J)=RAN(ISEED)
RETURN
END

```

Appendix B. Stopping Criteria Formulations

This section lists the mathematical formulation of the stopping criteria evaluated in the artificial neural network (ANN).

- **Classification Error Rate**

The classification error rate is evaluated for the training and testing sets and is defined as follows:

$$R = \frac{c}{n}$$

where c is the number of exemplars classified correctly by the ANN and n is the total number of exemplars classified.

- **Weighted Average Error Rate**

Weighted average error rate is evaluated using both the training set and the testing set classification error rates as determined above. It is defined as follows:

$$WtAvg = p_{train} * R_{train} + p_{test} * R_{test}$$

where R_{train} is the classification error rate for the training set, R_{test} is the classification error rate for the testing set, p_{train} is the percentage weight assigned to the training set, and p_{test} is the percentage weight assigned to the testing set such that

$$p_{train} + p_{test} = 1$$

- **Moving Average Error Rate**

Moving average error rate is evaluated using the testing set over the last Int epochs and is defined as follows:

$$MovAvg = \sum_i^{Int} \frac{R_i}{Int}$$

where R_i is the classification error rate for the testing set.

- **Total Absolute Error**

Total absolute error is evaluated on the testing set and is defined as follows:

$$E = \sum_i^n |y_i - d_i|$$

where y_i is the ANN output for exemplar i , d_i is the known, desired output for exemplar i , and n is the number of testing exemplars.

- **Error Sum of Squares**

Error sum of squares is evaluated on the testing set and is defined as follows:

$$ESS = \sum_i (y_i - d_i)^2$$

where y_i is the ANN output for exemplar i , d_i is the known, desired output for exemplar i , and n is the number of testing exemplars.

- **Largest Absolute Error**

Largest absolute error is evaluated on the testing set and is defined as follows:

$$LAE = \max |y_i - d_i|$$

where y_i is the ANN output for exemplar i , d_i is the known, desired output for exemplar i , and n is the number of testing exemplars.

- **Absolute Weight Change**

Absolute weight change is defined as follows:

$$AWC = \sum_{k=1}^m |w_k(t+1) - w_k(t)|$$

where m is the total number of weights and w_k is the weight of neuron k for the t th epoch.

- **Squared Weight Change**

Squared weight change is defined as follows:

$$SWC = \sum_{k=1}^m [w_k(t+1) - w_k(t)]^2$$

where m is the total number of weights and w_k is the weight of neuron k for the t th epoch.

- **Relative Weight Change**

Relative weight change is defined as follows:

$$RWC = \sum_{k=1}^m \frac{|w_k(t+1) - w_k(t)|}{|w_k(t)|}$$

where m is the total number of weights and w_k is the weight of neuron k for the t th epoch.

- **Mean Weight Change**

Mean weight change is defined as follows:

$$MWC = \frac{\sum_{k=1}^m |w_k(t+1) - w_k(t)|}{m}$$

where m is the total number of weights and w_k is the weight of neuron k for the t th epoch.

Appendix C. Total Absolute Error Function in the XOR Problem

This appendix shows the function of total absolute error for the four cases which did not meet the thresholds of the third experiment. They are listed by the replication number (out of ten replications) in which they occurred.

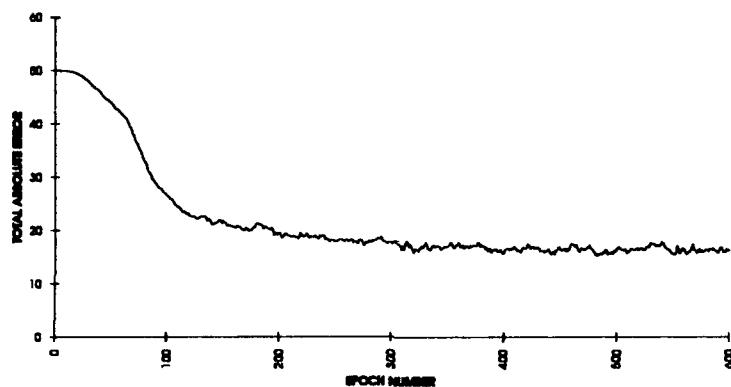


Figure 42. Replication One Total Absolute Error

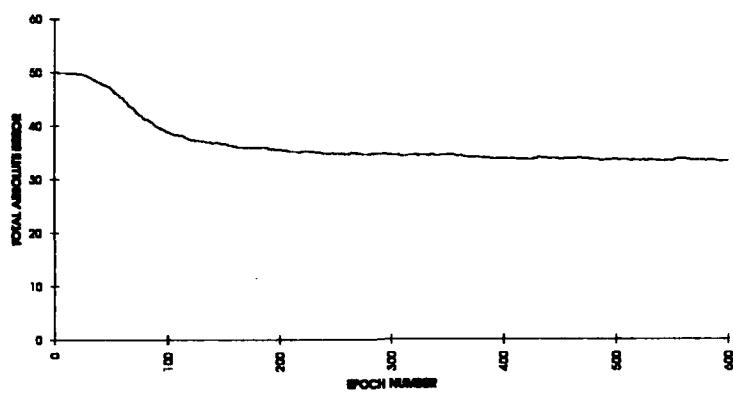


Figure 43. Replication Four Total Absolute Error

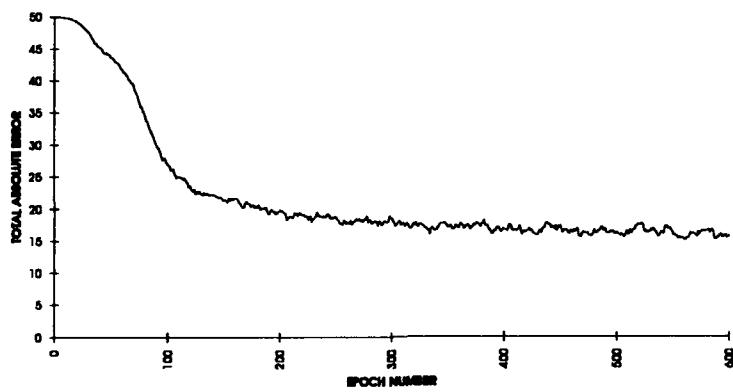


Figure 44. Replication Eight Total Absolute Error

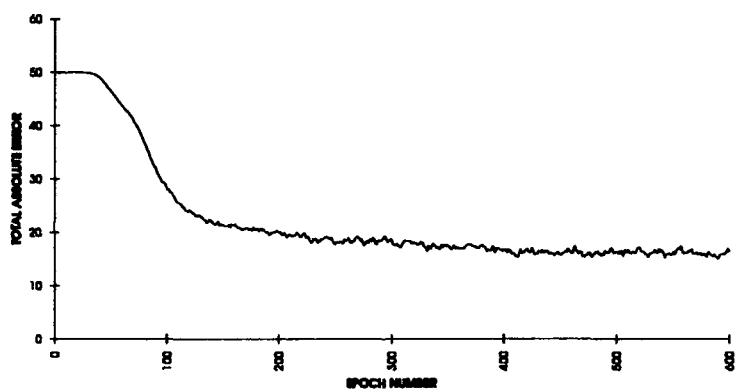


Figure 45. Replication Nine Total Absolute Error

Appendix D. Mesh Problem: An Output Comparison

This chapter contains the raw data for the mesh problem. The artificial neural network was trained for up to 15,000 epochs. The number of hidden nodes was set at all even numbers from four to twenty (inclusive). At each level of hidden nodes, ten replications of the training were conducted. In the Tables which follow, the asterisks (*) indicate those values selected by the heuristic rules given in Chapter 4.

Table 6: Four Hidden Node Output

| Cycle | Statistic | Epoch | Statistic | Val Set Error Rate | Ave Error Rate or Std Dev | Select Ave Er Rat or St Dev |
|---------------------|-----------|-------|-----------|--------------------|---------------------------|-----------------------------|
| Training Set | | | | | | |
| 1* | 0.1200 | 2901 | 0.1200 | 0.2183 | 0.2617 | 0.2294 |
| 2* | 0.1100 | 13920 | 0.1100 | 0.2200 | | |
| 3 | 0.1600 | 12727 | 0.1600 | 0.2633 | 0.0466 | 0.0142 |
| 4 | 0.2000 | 9462 | 0.2000 | 0.3250 | | |
| 5* | 0.1200 | 13633 | 0.1200 | 0.2200 | | |
| 6 | 0.1900 | 14328 | 0.1900 | 0.3300 | | |
| 7* | 0.1100 | 12431 | 0.1100 | 0.2450 | | |
| 8* | 0.1200 | 11577 | 0.1200 | 0.2233 | | |
| 9 | 0.1800 | 6552 | 0.1800 | 0.3217 | | |
| 10* | 0.1200 | 9652 | 0.1200 | 0.2500 | | |
| Testing Set | | | | | | |
| 1* | 0.2300 | 3047 | 0.2300 | 0.2050 | 0.2532 | 0.2217 |
| 2* | 0.2300 | 1091 | 0.2300 | 0.2067 | | |
| 3* | 0.2500 | 4632 | 0.2500 | 0.2667 | 0.0543 | 0.0236 |
| 4 | 0.3700 | 10121 | 0.3700 | 0.3233 | | |
| 5* | 0.2300 | 2697 | 0.2300 | 0.2000 | | |
| 6 | 0.3700 | 10951 | 0.3700 | 0.3250 | | |
| 7* | 0.2400 | 995 | 0.2400 | 0.2317 | | |
| 8* | 0.2400 | 669 | 0.2400 | 0.2100 | | |
| 9 | 0.3700 | 2614 | 0.3700 | 0.3317 | | |
| 10* | 0.2400 | 933 | 0.2400 | 0.2317 | | |

Table 6: Four Hidden Node Output (continued)

| Cycle | Statistic | Epoch | Statistic | Val Set Error Rate | Ave Error Rate or Std Dev | Select Ave Err Rat or St Dev |
|-----------------------------|-----------|-------|-----------|--------------------------|---------------------------------|------------------------------------|
| Weighted Average | | | | | | |
| 1* | 0.1850 | 2901 | 0.1850 | 0.2183 | 0.2568 | 0.2204 |
| 2* | 0.1850 | 1906 | 0.1850 | 0.2183 | | |
| 3 | 0.2100 | 12727 | 0.2100 | 0.2633 | 0.0497 | 0.0025 |
| 4 | 0.2900 | 9462 | 0.2900 | 0.3250 | | |
| 5 | 0.2050 | 6341 | 0.2050 | 0.2050 | | |
| 6 | 0.2850 | 14536 | 0.2850 | 0.3283 | | |
| 7* | 0.1950 | 1188 | 0.1950 | 0.2217 | | |
| 8* | 0.1900 | 11577 | 0.1900 | 0.2233 | | |
| 9 | 0.2850 | 6552 | 0.2850 | 0.3217 | | |
| 10 | 0.2000 | 14949 | 0.2000 | 0.2433 | | |
| Moving Average | | | | | | |
| 1* | 0.2400 | 3139 | 0.2400 | 0.2167 | 0.2553 | 0.2255 |
| 2* | 0.2360 | 1101 | 0.2360 | 0.2100 | | |
| 3* | 0.2520 | 6132 | 0.2520 | 0.2633 | 0.0505 | 0.0187 |
| 4 | 0.3760 | 11693 | 0.3760 | 0.3200 | | |
| 5* | 0.2540 | 2700 | 0.2540 | 0.2083 | | |
| 6 | 0.3740 | 13176 | 0.3740 | 0.3233 | | |
| 7* | 0.2500 | 1038 | 0.2500 | 0.2250 | | |
| 8* | 0.2400 | 13109 | 0.2400 | 0.2233 | | |
| 9 | 0.3780 | 2614 | 0.3780 | 0.3317 | | |
| 10* | 0.2500 | 924 | 0.2500 | 0.2317 | | |
| Total Absolute Error | | | | | | |
| 1* | 28.9528 | 6125 | 28.9528 | 0.2067 | 0.2578 | 0.2230 |
| 2* | 29.4051 | 5349 | 29.4051 | 0.2067 | | |
| 3* | 28.2199 | 14052 | 28.2199 | 0.2683 | 0.0512 | 0.0263 |
| 4 | 42.8098 | 10456 | 42.8098 | 0.3250 | | |
| 5* | 29.3826 | 6335 | 29.3826 | 0.2100 | | |
| 6 | 42.9163 | 12987 | 42.9163 | 0.3250 | | |
| 7 | 30.7562 | 12501 | 30.7562 | 0.2417 | | |
| 8* | 26.6532 | 14685 | 26.6532 | 0.2233 | | |
| 9 | 42.5929 | 14058 | 42.5929 | 0.3300 | | |
| 10 | 30.7660 | 11150 | 30.7660 | 0.2417 | | |

Table 7: Six Hidden Node Output

| Cycle | Statistic | Epoch | Statistic | Val Set Error Rate | Ave Error Rate or Std Dev | Select Ave Er Rat or St Dev |
|-------------------------|-----------|-------|-----------|--------------------|---------------------------|-----------------------------|
| Training Set | | | | | | |
| 1 | 0.1100 | 4268 | 0.1100 | 0.2167 | 0.1873 | 0.1588 |
| 2 | 0.1000 | 14096 | 0.1000 | 0.1983 | | |
| 3 | 0.1000 | 12515 | 0.1000 | 0.1933 | 0.0301 | 0.0270 |
| 4* | 0.0800 | 5381 | 0.0800 | 0.1733 | | |
| 5 | 0.1000 | 14756 | 0.1000 | 0.2033 | | |
| 6* | 0.0700 | 10709 | 0.0700 | 0.1717 | | |
| 7 | 0.1000 | 11960 | 0.1000 | 0.2067 | | |
| 8* | 0.0700 | 5688 | 0.0700 | 0.1183 | | |
| 9 | 0.1200 | 2317 | 0.1200 | 0.2200 | | |
| 10* | 0.0800 | 6254 | 0.0800 | 0.1717 | | |
| Testing Set | | | | | | |
| 1 | 0.2100 | 10493 | 0.2100 | 0.1967 | 0.1760 | 0.1570 |
| 2 | 0.2100 | 6931 | 0.2100 | 0.1917 | | |
| 3 | 0.2000 | 4302 | 0.2000 | 0.1933 | 0.0317 | 0.0367 |
| 4* | 0.1900 | 1680 | 0.1900 | 0.1783 | | |
| 5 | 0.2000 | 5321 | 0.2000 | 0.1917 | | |
| 6* | 0.1800 | 1606 | 0.1800 | 0.1600 | | |
| 7 | 0.2400 | 3144 | 0.2400 | 0.2017 | | |
| 8* | 0.1000 | 2787 | 0.1000 | 0.0933 | | |
| 9* | 0.1800 | 12483 | 0.1800 | 0.1833 | | |
| 10* | 0.1900 | 3620 | 0.1900 | 0.1700 | | |
| Weighted Average | | | | | | |
| 1 | 0.1750 | 14450 | 0.1750 | 0.1900 | 0.1763 | 0.1508 |
| 2 | 0.1750 | 7333 | 0.1750 | 0.1933 | | |
| 3 | 0.1650 | 12515 | 0.1650 | 0.1933 | 0.0304 | 0.0351 |
| 4* | 0.1500 | 3520 | 0.1500 | 0.1667 | | |
| 5 | 0.1750 | 13151 | 0.1750 | 0.1933 | | |
| 6* | 0.1450 | 10709 | 0.1450 | 0.1717 | | |
| 7 | 0.1950 | 11960 | 0.1950 | 0.2067 | | |
| 8* | 0.1100 | 2744 | 0.1100 | 0.0983 | | |
| 9 | 0.1900 | 12546 | 0.1900 | 0.1833 | | |
| 10* | 0.1400 | 12376 | 0.1400 | 0.1667 | | |

Table 7: Six Hidden Node Output (continued)

| Cycle | Statistic | Epoch | Statistic | Val Set Error Rate | Ave Error Rate or Std Dev | Select Ave Er Rat or St Dev |
|-----------------------------|-----------|-------|-----------|--------------------------|---------------------------------|-----------------------------------|
| Moving Average | | | | | | |
| 1 | 0.2220 | 13846 | 0.2220 | 0.1917 | 0.1778 | 0.1458 |
| 2 | 0.2280 | 9527 | 0.2280 | 0.1950 | | |
| 3 | 0.2200 | 12501 | 0.2200 | 0.1933 | 0.0361 | 0.0339 |
| 4* | 0.1920 | 9268 | 0.1920 | 0.1633 | | |
| 5 | 0.2140 | 5325 | 0.2140 | 0.1883 | | |
| 6* | 0.1840 | 1756 | 0.1840 | 0.1633 | | |
| 7 | 0.2520 | 1503 | 0.2520 | 0.2333 | | |
| 8* | 0.1100 | 2791 | 0.1100 | 0.0950 | | |
| 9 | 0.2220 | 12486 | 0.2220 | 0.1933 | | |
| 10* | 0.1900 | 9089 | 0.1900 | 0.1617 | | |
| Total Absolute Error | | | | | | |
| 1 | 27.0278 | 13998 | 27.0278 | 0.1917 | 0.1743 | 0.1479 |
| 2 | 27.2391 | 11172 | 27.2391 | 0.1933 | | |
| 3 | 27.0533 | 12920 | 27.0533 | 0.1883 | 0.0298 | 0.0320 |
| 4* | 21.0477 | 9262 | 21.0477 | 0.1633 | | |
| 5 | 26.8933 | 14383 | 26.8933 | 0.1950 | | |
| 6* | 21.5338 | 6861 | 21.5338 | 0.1633 | | |
| 7 | 28.7017 | 4507 | 28.7017 | 0.2033 | | |
| 8* | 15.9658 | 4120 | 15.9658 | 0.1000 | | |
| 9 | 25.1477 | 12547 | 25.1477 | 0.1800 | | |
| 10* | 21.2537 | 10817 | 21.2537 | 0.1650 | | |

Table 8: Eight Hidden Node Output

| Cycle | Statistic | Epoch | Statistic | Val Set Error Rate | Ave Error Rate or Std Dev | Select Ave Er Rat or St Dev |
|-------------------------|-----------|-------|-----------|--------------------|---------------------------|-----------------------------|
| Training Set | | | | | | |
| 1 | 0.0700 | 10623 | 0.0700 | 0.1367 | 0.1655 | 0.1267 |
| 2 | 0.1200 | 1560 | 0.1200 | 0.2117 | | |
| 3* | 0.0400 | 8544 | 0.0400 | 0.1050 | 0.0464 | 0.0390 |
| 4 | 0.0800 | 7283 | 0.0800 | 0.1683 | | |
| 5 | 0.0700 | 7996 | 0.0700 | 0.1317 | | |
| 6 | 0.1000 | 13383 | 0.1000 | 0.2283 | | |
| 7* | 0.0400 | 5114 | 0.0400 | 0.1033 | | |
| 8 | 0.1100 | 12596 | 0.1100 | 0.2267 | | |
| 9 | 0.0800 | 4876 | 0.0800 | 0.1717 | | |
| 10* | 0.0500 | 13401 | 0.0500 | 0.1717 | | |
| Testing Set | | | | | | |
| 1 | 0.1800 | 5600 | 0.1800 | 0.1267 | 0.1592 | 0.0967 |
| 2 | 0.2300 | 6459 | 0.2300 | 0.2117 | | |
| 3* | 0.1400 | 8028 | 0.1400 | 0.1050 | 0.0458 | 0.0118 |
| 4 | 0.1800 | 2530 | 0.1800 | 0.1650 | | |
| 5 | 0.1900 | 2983 | 0.1900 | 0.1383 | | |
| 6 | 0.2300 | 1635 | 0.2300 | 0.2150 | | |
| 7* | 0.0800 | 9827 | 0.0800 | 0.0883 | | |
| 8 | 0.2300 | 6780 | 0.2300 | 0.2183 | | |
| 9 | 0.1900 | 4199 | 0.1900 | 0.1667 | | |
| 10 | 0.1800 | 1980 | 0.1800 | 0.1567 | | |
| Weighted Average | | | | | | |
| 1 | 0.1450 | 4977 | 0.1450 | 0.1333 | 0.1600 | 0.0992 |
| 2 | 0.1850 | 1560 | 0.1850 | 0.2117 | | |
| 3* | 0.0950 | 8544 | 0.0950 | 0.1050 | 0.0456 | 0.0082 |
| 4 | 0.1450 | 13710 | 0.1450 | 0.1583 | | |
| 5 | 0.1400 | 7996 | 0.1400 | 0.1317 | | |
| 6 | 0.1800 | 8609 | 0.1800 | 0.2217 | | |
| 7* | 0.0800 | 12393 | 0.0800 | 0.0933 | | |
| 8 | 0.1900 | 2252 | 0.1900 | 0.2167 | | |
| 9 | 0.1400 | 14239 | 0.1400 | 0.1617 | | |
| 10 | 0.1400 | 11736 | 0.1400 | 0.1667 | | |

Table 8: Eight Hidden Node Output (continued)

| Cycle | Statistic | Epoch | Statistic | Val Set Error Rate | Ave Error Rate or Std Dev | Select Ave Er Rat or St Dev |
|-----------------------------|-----------|-------|-----------|--------------------|---------------------------|-----------------------------|
| Moving Average | | | | | | |
| 1 | 0.1920 | 10122 | 0.1920 | 0.1333 | 0.1598 | 0.1000 |
| 2 | 0.2400 | 8494 | 0.2400 | 0.2250 | | |
| 3* | 0.1400 | 8416 | 0.1400 | 0.1067 | 0.0476 | 0.0094 |
| 4 | 0.1880 | 14258 | 0.1880 | 0.1533 | | |
| 5 | 0.1960 | 5704 | 0.1960 | 0.1300 | | |
| 6 | 0.2400 | 8828 | 0.2400 | 0.2250 | | |
| 7* | 0.0900 | 2142 | 0.0900 | 0.0933 | | |
| 8 | 0.2360 | 7113 | 0.2360 | 0.2150 | | |
| 9 | 0.1900 | 6265 | 0.1900 | 0.1600 | | |
| 10 | 0.1860 | 1984 | 0.1860 | 0.1567 | | |
| Total Absolute Error | | | | | | |
| 1 | 20.1558 | 7109 | 20.1558 | 0.1267 | 0.1592 | 0.1000 |
| 2 | 25.3412 | 10949 | 25.3412 | 0.1967 | | |
| 3* | 15.3280 | 13261 | 15.3280 | 0.1050 | 0.0465 | 0.0071 |
| 4 | 20.6984 | 14981 | 20.6984 | 0.1517 | | |
| 5 | 20.7916 | 7965 | 20.7916 | 0.1283 | | |
| 6 | 27.2794 | 14380 | 27.2794 | 0.2200 | | |
| 7* | 12.9566 | 12416 | 12.9566 | 0.0950 | | |
| 8 | 27.7513 | 13800 | 27.7513 | 0.2300 | | |
| 9 | 21.2363 | 12660 | 21.2363 | 0.1683 | | |
| 10 | 22.2873 | 14104 | 22.2873 | 0.1700 | | |

Table 9: Ten Hidden Node Output

| Cycle | Statistic | Epoch | Statistic | Val Set Error Rate | Ave Error Rate or Std Dev | Select Ave Er Rat or St Dev |
|-------------------------|-----------|-------|-----------|--------------------|---------------------------|-----------------------------|
| Training Set | | | | | | |
| 1* | 0.0400 | 14314 | 0.0400 | 0.0883 | 0.1477 | 0.0894 |
| 2 | 0.1100 | 14956 | 0.1100 | 0.1750 | | |
| 3* | 0.0400 | 14646 | 0.0400 | 0.0817 | 0.0457 | 0.0386 |
| 4 | 0.0900 | 13296 | 0.0900 | 0.1733 | | |
| 5 | 0.0700 | 10135 | 0.0700 | 0.1550 | | |
| 6 | 0.1100 | 12183 | 0.1100 | 0.2100 | | |
| 7 | 0.0700 | 7521 | 0.0700 | 0.1517 | | |
| 8* | 0.0400 | 9619 | 0.0400 | 0.0983 | | |
| 9 | 0.0600 | 5310 | 0.0600 | 0.1400 | | |
| 10 | 0.0800 | 6088 | 0.0800 | 0.2033 | | |
| Testing Set | | | | | | |
| 1* | 0.0900 | 10849 | 0.0900 | 0.0800 | 0.1437 | 0.0861 |
| 2 | 0.2200 | 11701 | 0.2200 | 0.1717 | | |
| 3* | 0.0800 | 6059 | 0.0800 | 0.0933 | 0.0446 | 0.0067 |
| 4 | 0.2000 | 4383 | 0.2000 | 0.1850 | | |
| 5 | 0.1800 | 5358 | 0.1800 | 0.1283 | | |
| 6 | 0.2200 | 2868 | 0.2200 | 0.2017 | | |
| 7 | 0.1900 | 2844 | 0.1900 | 0.1533 | | |
| 8* | 0.0900 | 12581 | 0.0900 | 0.0850 | | |
| 9 | 0.1700 | 1779 | 0.1700 | 0.1550 | | |
| 10 | 0.2200 | 3164 | 0.2200 | 0.1833 | | |
| Weighted Average | | | | | | |
| 1* | 0.0800 | 12577 | 0.0800 | 0.0950 | 0.1448 | 0.0917 |
| 2 | 0.1750 | 14956 | 0.1750 | 0.1750 | | |
| 3* | 0.0850 | 6272 | 0.0850 | 0.0850 | 0.0424 | 0.0058 |
| 4 | 0.1600 | 5758 | 0.1600 | 0.1833 | | |
| 5 | 0.1400 | 6329 | 0.1400 | 0.1350 | | |
| 6 | 0.1800 | 14428 | 0.1800 | 0.2050 | | |
| 7 | 0.1400 | 10518 | 0.1400 | 0.1517 | | |
| 8* | 0.0850 | 14394 | 0.0850 | 0.0950 | | |
| 9 | 0.1300 | 5310 | 0.1300 | 0.1400 | | |
| 10 | 0.1800 | 3392 | 0.1800 | 0.1833 | | |

Table 9: Ten Hidden Node Output (continued)

| Cycle | Statistic | Epoch | Statistic | Val Set Error Rate | Ave Error Rate or Std Dev | Select Ave Er Rat or St Dev |
|-----------------------------|-----------|-------|-----------|--------------------------|---------------------------------|-----------------------------------|
| Moving Average | | | | | | |
| 1* | 0.1000 | 13057 | 0.1000 | 0.0900 | 0.1455 | 0.0900 |
| 2 | 0.2340 | 12268 | 0.2340 | 0.1783 | | |
| 3* | 0.0920 | 6068 | 0.0920 | 0.0867 | 0.0441 | 0.0033 |
| 4 | 0.2100 | 4386 | 0.2100 | 0.1900 | | |
| 5 | 0.1960 | 6333 | 0.1960 | 0.1383 | | |
| 6 | 0.2320 | 2869 | 0.2320 | 0.2067 | | |
| 7 | 0.1960 | 14940 | 0.1960 | 0.1383 | | |
| 8* | 0.0960 | 12585 | 0.0960 | 0.0933 | | |
| 9 | 0.1700 | 1978 | 0.1700 | 0.1517 | | |
| 10 | 0.2200 | 3337 | 0.2200 | 0.1817 | | |
| Total Absolute Error | | | | | | |
| 1* | 13.4608 | 13345 | 13.4608 | 0.0883 | 0.1450 | 0.0883 |
| 2 | 27.3778 | 12622 | 27.3778 | 0.1767 | | |
| 3* | 13.0426 | 9083 | 13.0426 | 0.0883 | 0.0477 | 0.0000 |
| 4 | 24.3949 | 14578 | 24.3949 | 0.1767 | | |
| 5 | 21.0033 | 7629 | 21.0033 | 0.1317 | | |
| 6 | 27.1659 | 14722 | 27.1659 | 0.2017 | | |
| 7 | 21.3834 | 14936 | 21.3834 | 0.1350 | | |
| 8* | 13.3277 | 14892 | 13.3277 | 0.0883 | | |
| 9 | 20.2756 | 12328 | 20.2756 | 0.1450 | | |
| 10 | 28.3567 | 12965 | 28.3567 | 0.2183 | | |

Table 10: Twelve Hidden Node Output

| Cycle | Statistic | Epoch | Statistic | Val Set Error Rate | Ave Error Rate or Std Dev | Select Ave Er Rat or St Dev |
|-------------------------|-----------|-------|-----------|--------------------------|---------------------------------|-----------------------------------|
| Training Set | | | | | | |
| 1* | 0.040 | 5120 | 0.040 | 0.0983 | 0.1517 | 0.1253 |
| 2* | 0.050 | 4331 | 0.050 | 0.1600 | | |
| 3* | 0.060 | 8676 | 0.060 | 0.1417 | 0.0438 | 0.0322 |
| 4 | 0.080 | 10609 | 0.080 | 0.2150 | | |
| 5* | 0.050 | 11658 | 0.050 | 0.1600 | | |
| 6 | 0.110 | 10718 | 0.110 | 0.1850 | | |
| 7 | 0.090 | 4073 | 0.090 | 0.2033 | | |
| 8* | 0.050 | 13766 | 0.050 | 0.1000 | | |
| 9* | 0.040 | 3997 | 0.040 | 0.0917 | | |
| 10 | 0.070 | 4663 | 0.070 | 0.1617 | | |
| Testing Set | | | | | | |
| 1* | 0.080 | 2344 | 0.080 | 0.0983 | 0.1433 | 0.0933 |
| 2 | 0.190 | 1386 | 0.190 | 0.1767 | | |
| 3 | 0.150 | 2411 | 0.150 | 0.1383 | 0.0404 | 0.0101 |
| 4 | 0.200 | 2071 | 0.200 | 0.1817 | | |
| 5 | 0.200 | 3565 | 0.200 | 0.1517 | | |
| 6 | 0.230 | 5501 | 0.230 | 0.1850 | | |
| 7 | 0.220 | 2501 | 0.220 | 0.1917 | | |
| 8* | 0.090 | 14588 | 0.090 | 0.0817 | | |
| 9* | 0.060 | 3033 | 0.060 | 0.1000 | | |
| 10 | 0.180 | 8372 | 0.180 | 0.1283 | | |
| Weighted Average | | | | | | |
| 1* | 0.080 | 5120 | 0.080 | 0.0983 | 0.1437 | 0.0944 |
| 2 | 0.135 | 1953 | 0.135 | 0.1517 | | |
| 3 | 0.130 | 2222 | 0.130 | 0.1500 | 0.0379 | 0.0035 |
| 4 | 0.170 | 2370 | 0.170 | 0.1833 | | |
| 5 | 0.145 | 3584 | 0.145 | 0.1617 | | |
| 6 | 0.180 | 12804 | 0.180 | 0.1717 | | |
| 7 | 0.190 | 2536 | 0.190 | 0.1967 | | |
| 8* | 0.090 | 14733 | 0.090 | 0.0933 | | |
| 9* | 0.070 | 3997 | 0.070 | 0.0917 | | |
| 10 | 0.140 | 9873 | 0.140 | 0.1383 | | |

Table 10: Twelve Hidden Node Output (continued)

| Cycle | Statistic | Epoch | Statistic | Val Set Error Rate | Ave Error Rate or Std Dev | Select Ave Er Rat or St Dev |
|-----------------------------|-----------|-------|-----------|--------------------------|---------------------------------|-----------------------------------|
| Moving Average | | | | | | |
| 1* | 0.086 | 3180 | 0.086 | 0.0983 | 0.1433 | 0.1025 |
| 2 | 0.190 | 1702 | 0.190 | 0.1600 | | |
| 3 | 0.164 | 2484 | 0.164 | 0.1350 | 0.0371 | 0.0059 |
| 4 | 0.200 | 2371 | 0.200 | 0.1767 | | |
| 5 | 0.204 | 3568 | 0.204 | 0.1567 | | |
| 6 | 0.246 | 10999 | 0.246 | 0.1767 | | |
| 7 | 0.230 | 2509 | 0.230 | 0.1983 | | |
| 8 | 0.108 | 14592 | 0.108 | 0.0867 | | |
| 9* | 0.074 | 2429 | 0.074 | 0.1067 | | |
| 10 | 0.194 | 13562 | 0.194 | 0.1383 | | |
| Total Absolute Error | | | | | | |
| 1* | 11.4825 | 13797 | 11.4825 | 0.0867 | 0.1385 | 0.0817 |
| 2 | 22.4609 | 4793 | 22.4609 | 0.1517 | | |
| 3 | 17.8558 | 7120 | 17.8558 | 0.1367 | 0.0442 | 0.0044 |
| 4 | 27.6511 | 2908 | 27.6511 | 0.1883 | | |
| 5 | 24.0679 | 3856 | 24.0679 | 0.1533 | | |
| 6 | 27.8478 | 12823 | 27.8478 | 0.1900 | | |
| 7 | 28.2915 | 5535 | 28.2915 | 0.1867 | | |
| 8* | 14.6244 | 14642 | 14.6244 | 0.0783 | | |
| 9* | 12.1035 | 6003 | 12.1035 | 0.0800 | | |
| 10 | 20.1519 | 12839 | 20.1519 | 0.1333 | | |

Table 11: Fourteen Hidden Node Output

| Cycle | Statistic | Epoch | Statistic | Val Set Error Rate | Ave Error Rate or Std Dev | Select Ave Er Rat or St Dev |
|-------------------------|-----------|-------|-----------|--------------------|---------------------------|-----------------------------|
| Training Set | | | | | | |
| 1 | 0.070 | 14252 | 0.070 | 0.2133 | 0.1593 | 0.1504 |
| 2* | 0.060 | 12640 | 0.060 | 0.1717 | | |
| 3* | 0.050 | 10388 | 0.050 | 0.1583 | 0.0269 | 0.0195 |
| 4* | 0.060 | 12171 | 0.060 | 0.1300 | | |
| 5 | 0.090 | 9264 | 0.090 | 0.1767 | | |
| 6* | 0.060 | 9614 | 0.060 | 0.1550 | | |
| 7* | 0.060 | 9878 | 0.060 | 0.1450 | | |
| 8* | 0.060 | 3681 | 0.060 | 0.1683 | | |
| 9* | 0.050 | 6284 | 0.050 | 0.1150 | | |
| 10* | 0.060 | 7325 | 0.060 | 0.1600 | | |
| Testing Set | | | | | | |
| 1 | 0.230 | 2775 | 0.230 | 0.2050 | 0.1487 | 0.1333 |
| 2 | 0.200 | 3142 | 0.200 | 0.1600 | | |
| 3* | 0.160 | 2266 | 0.160 | 0.1400 | 0.0312 | 0.0284 |
| 4* | 0.160 | 14069 | 0.160 | 0.1167 | | |
| 5* | 0.170 | 7255 | 0.170 | 0.1633 | | |
| 6 | 0.200 | 9747 | 0.200 | 0.1500 | | |
| 7 | 0.180 | 4944 | 0.180 | 0.1300 | | |
| 8 | 0.180 | 1579 | 0.180 | 0.1750 | | |
| 9* | 0.110 | 6161 | 0.110 | 0.0933 | | |
| 10* | 0.160 | 2726 | 0.160 | 0.1533 | | |
| Weighted Average | | | | | | |
| 1 | 0.180 | 13910 | 0.180 | 0.1900 | 0.1518 | 0.1278 |
| 2 | 0.145 | 3131 | 0.145 | 0.1667 | | |
| 3* | 0.125 | 5354 | 0.125 | 0.1533 | 0.0247 | 0.0231 |
| 4* | 0.125 | 13771 | 0.125 | 0.1217 | | |
| 5 | 0.140 | 10468 | 0.140 | 0.1600 | | |
| 6 | 0.140 | 14571 | 0.140 | 0.1483 | | |
| 7 | 0.145 | 4971 | 0.145 | 0.1333 | | |
| 8 | 0.150 | 1720 | 0.150 | 0.1733 | | |
| 9* | 0.090 | 12326 | 0.090 | 0.1083 | | |
| 10 | 0.145 | 2839 | 0.145 | 0.1633 | | |

Table 11: Fourteen Hidden Node Output (continued)

| Cycle | Statistic | Epoch | Statistic | Val Set Error Rate | Ave Error Rate or Std Dev | Select Ave Er Rat or St Dev |
|-----------------------------|-----------|-------|-----------|--------------------|---------------------------|-----------------------------|
| Moving Average | | | | | | |
| 1 | 0.244 | 2964 | 0.244 | 0.2067 | 0.1517 | 0.1194 |
| 2 | 0.208 | 3145 | 0.208 | 0.1633 | | |
| 3* | 0.170 | 2270 | 0.170 | 0.1417 | 0.0309 | 0.0210 |
| 4* | 0.166 | 14989 | 0.166 | 0.1167 | | |
| 5 | 0.182 | 7282 | 0.182 | 0.1667 | | |
| 6 | 0.214 | 9083 | 0.214 | 0.1500 | | |
| 7 | 0.188 | 4947 | 0.188 | 0.1317 | | |
| 8 | 0.188 | 1581 | 0.188 | 0.1783 | | |
| 9* | 0.116 | 8997 | 0.116 | 0.1000 | | |
| 10 | 0.186 | 2730 | 0.186 | 0.1617 | | |
| Total Absolute Error | | | | | | |
| 1 | 27.8979 | 13187 | 27.8979 | 0.2017 | 0.1493 | 0.1183 |
| 2 | 24.0182 | 12284 | 24.0182 | 0.1650 | | |
| 3* | 17.9408 | 4484 | 17.9408 | 0.1350 | 0.0288 | 0.0176 |
| 4* | 18.7044 | 14986 | 18.7044 | 0.1200 | | |
| 5 | 20.4197 | 7674 | 20.4197 | 0.1633 | | |
| 6 | 23.0643 | 6470 | 23.0643 | 0.1650 | | |
| 7 | 20.2532 | 13232 | 20.2532 | 0.1300 | | |
| 8 | 22.2750 | 6451 | 22.2750 | 0.1617 | | |
| 9* | 12.2425 | 9226 | 12.2425 | 0.1000 | | |
| 10 | 22.1440 | 2792 | 22.1440 | 0.1517 | | |

Table 12: Sixteen Hidden Node Output

| Cycle | Statistic | Epoch | Statistic | Val Set Error Rate | Ave Error Rate or Std Dev | Select Ave Er Rat or St Dev |
|-------------------------|-----------|-------|-----------|--------------------|---------------------------|-----------------------------|
| Training Set | | | | | | |
| 1* | 0.0600 | 9797 | 0.0600 | 0.1567 | 0.1415 | 0.1381 |
| 2* | 0.0500 | 10465 | 0.0500 | 0.1100 | | |
| 3* | 0.0600 | 6068 | 0.0600 | 0.1617 | 0.0291 | 0.0288 |
| 4* | 0.0500 | 7361 | 0.0500 | 0.1733 | | |
| 5* | 0.0500 | 12999 | 0.0500 | 0.1500 | | |
| 6* | 0.0600 | 10537 | 0.0600 | 0.1600 | | |
| 7* | 0.0500 | 4389 | 0.0500 | 0.1017 | | |
| 8* | 0.0400 | 8959 | 0.0400 | 0.1333 | | |
| 9 | 0.0800 | 13681 | 0.0800 | 0.1717 | | |
| 10* | 0.0500 | 7032 | 0.0500 | 0.0967 | | |
| Testing Set | | | | | | |
| 1 | 0.1700 | 3268 | 0.1700 | 0.1433 | 0.1293 | 0.1133 |
| 2* | 0.1300 | 12350 | 0.1300 | 0.1050 | | |
| 3 | 0.1900 | 14776 | 0.1900 | 0.1450 | 0.0314 | 0.0145 |
| 4 | 0.2100 | 3584 | 0.2100 | 0.1650 | | |
| 5* | 0.1500 | 9371 | 0.1500 | 0.1350 | | |
| 6 | 0.1700 | 2910 | 0.1700 | 0.1400 | | |
| 7* | 0.1200 | 6386 | 0.1200 | 0.1050 | | |
| 8* | 0.1400 | 10793 | 0.1400 | 0.1083 | | |
| 9 | 0.2100 | 1620 | 0.2100 | 0.1750 | | |
| 10 | 0.0700 | 14970 | 0.0700 | 0.0717 | | |
| Weighted Average | | | | | | |
| 1 | 0.1300 | 3354 | 0.1300 | 0.1383 | 0.1343 | 0.1120 |
| 2* | 0.1050 | 11985 | 0.1050 | 0.1133 | | |
| 3 | 0.1400 | 14520 | 0.1400 | 0.1467 | 0.0299 | 0.0239 |
| 4 | 0.1450 | 7361 | 0.1450 | 0.1733 | | |
| 5* | 0.1150 | 12999 | 0.1150 | 0.1500 | | |
| 6 | 0.1350 | 2173 | 0.1350 | 0.1617 | | |
| 7* | 0.1000 | 4389 | 0.1000 | 0.1017 | | |
| 8* | 0.1150 | 10870 | 0.1150 | 0.1100 | | |
| 9 | 0.1600 | 8522 | 0.1600 | 0.1633 | | |
| 10* | 0.0750 | 14701 | 0.0750 | 0.0850 | | |

Table 12: Sixteen Hidden Node Output (continued)

| Cycle | Statistic | Epoch | Statistic | Val Set Error Rate | Ave Error Rate or Std Dev | Select Ave Er Rat or St Dev |
|-----------------------------|-----------|-------|-----------|--------------------|---------------------------|-----------------------------|
| Moving Average | | | | | | |
| 1 | 0.1700 | 3334 | 0.1700 | 0.1383 | 0.1298 | 0.0971 |
| 2* | 0.1360 | 13962 | 0.1360 | 0.0950 | | |
| 3 | 0.2040 | 14725 | 0.2040 | 0.1417 | 0.0305 | 0.0103 |
| 4 | 0.2100 | 3926 | 0.2100 | 0.1700 | | |
| 5 | 0.1640 | 10265 | 0.1640 | 0.1400 | | |
| 6 | 0.1800 | 2133 | 0.1800 | 0.1600 | | |
| 7* | 0.1280 | 6386 | 0.1280 | 0.1050 | | |
| 8* | 0.1480 | 10797 | 0.1480 | 0.1050 | | |
| 9 | 0.2120 | 1982 | 0.2120 | 0.1600 | | |
| 10* | 0.0880 | 2743 | 0.0880 | 0.0833 | | |
| Total Absolute Error | | | | | | |
| 1 | 19.3845 | 3480 | 19.3845 | 0.1400 | 0.1325 | 0.1100 |
| 2* | 14.8096 | 14372 | 14.8096 | 0.1017 | | |
| 3 | 22.3533 | 14609 | 22.3533 | 0.1500 | 0.0292 | 0.0218 |
| 4 | 23.0003 | 8420 | 23.0003 | 0.1683 | | |
| 5* | 16.9740 | 12140 | 16.9740 | 0.1367 | | |
| 6 | 21.8437 | 2557 | 21.8437 | 0.1467 | | |
| 7* | 15.0910 | 10962 | 15.0910 | 0.1033 | | |
| 8* | 17.0449 | 3778 | 17.0449 | 0.1267 | | |
| 9 | 23.8317 | 1978 | 23.8317 | 0.1700 | | |
| 10* | 12.9401 | 14971 | 12.9401 | 0.0817 | | |

Table 13: Eighteen Hidden Node Output

| Cycle | Statistic | Epoch | Statistic | Val Set Error Rate | Ave Error Rate or Std Dev | Select Ave Er Rat or St Dev |
|-------------------------|-----------|-------|-----------|--------------------|---------------------------|-----------------------------|
| Training Set | | | | | | |
| 1* | 0.0600 | 3510 | 0.0600 | 0.1500 | 0.1293 | 0.1254 |
| 2* | 0.0500 | 6250 | 0.0500 | 0.1233 | | |
| 3 | 0.0800 | 9273 | 0.0800 | 0.1650 | 0.0186 | 0.0146 |
| 4* | 0.0500 | 8789 | 0.0500 | 0.1250 | | |
| 5* | 0.0500 | 13017 | 0.0500 | 0.1200 | | |
| 6* | 0.0500 | 7727 | 0.0500 | 0.1367 | | |
| 7* | 0.0400 | 8655 | 0.0400 | 0.1067 | | |
| 8* | 0.0500 | 4960 | 0.0500 | 0.1133 | | |
| 9* | 0.0500 | 4288 | 0.0500 | 0.1417 | | |
| 10* | 0.0400 | 5383 | 0.0400 | 0.1117 | | |
| Testing Set | | | | | | |
| 1 | 0.1600 | 2418 | 0.1600 | 0.1483 | 0.1172 | 0.0950 |
| 2* | 0.0900 | 13602 | 0.0900 | 0.0833 | | |
| 3 | 0.1700 | 10942 | 0.1700 | 0.1500 | 0.0281 | 0.0180 |
| 4* | 0.1000 | 11700 | 0.1000 | 0.0850 | | |
| 5 | 0.1400 | 11198 | 0.1400 | 0.1067 | | |
| 6 | 0.1600 | 3722 | 0.1600 | 0.1300 | | |
| 7* | 0.1000 | 10932 | 0.1000 | 0.0900 | | |
| 8* | 0.1000 | 2206 | 0.1000 | 0.1217 | | |
| 9 | 0.1600 | 2426 | 0.1600 | 0.1567 | | |
| 10 | 0.1200 | 11988 | 0.1200 | 0.1000 | | |
| Weighted Average | | | | | | |
| 1 | 0.1250 | 5392 | 0.1250 | 0.1333 | 0.1147 | 0.0977 |
| 2* | 0.0900 | 12769 | 0.0900 | 0.0933 | | |
| 3 | 0.1350 | 11610 | 0.1350 | 0.1550 | 0.0231 | 0.0163 |
| 4* | 0.0850 | 14917 | 0.0850 | 0.0717 | | |
| 5 | 0.1100 | 12743 | 0.1100 | 0.1150 | | |
| 6 | 0.1250 | 3737 | 0.1250 | 0.1283 | | |
| 7* | 0.0850 | 9390 | 0.0850 | 0.1017 | | |
| 8* | 0.0950 | 2548 | 0.0950 | 0.1100 | | |
| 9 | 0.1200 | 13327 | 0.1200 | 0.1267 | | |
| 10* | 0.1000 | 5383 | 0.1000 | 0.1117 | | |

Table 13: Eighteen Hidden Node Output (continued)

| Cycle | Statistic | Epoch | Statistic | Val Set Error Rate | Ave Error Rate or Std Dev | Select Ave Er Rat or St Dev |
|-----------------------------|-----------|-------|-----------|--------------------------|---------------------------------|-----------------------------------|
| Moving Average | | | | | | |
| 1 | 0.1620 | 5394 | 0.1620 | 0.1300 | 0.1143 | 0.0937 |
| 2* | 0.1100 | 13605 | 0.1100 | 0.0883 | | |
| 3 | 0.1780 | 10946 | 0.1780 | 0.1533 | 0.0252 | 0.0122 |
| 4* | 0.1060 | 14123 | 0.1060 | 0.0750 | | |
| 5 | 0.1480 | 13188 | 0.1480 | 0.1183 | | |
| 6 | 0.1600 | 3741 | 0.1600 | 0.1267 | | |
| 7* | 0.1120 | 14267 | 0.1120 | 0.0983 | | |
| 8* | 0.1060 | 2565 | 0.1060 | 0.1050 | | |
| 9 | 0.1600 | 2757 | 0.1600 | 0.1467 | | |
| 10* | 0.1200 | 14146 | 0.1200 | 0.1017 | | |
| Total Absolute Error | | | | | | |
| 1 | 16.9836 | 5399 | 16.9836 | 0.1350 | 0.1123 | 0.0900 |
| 2* | 12.0965 | 13602 | 12.0965 | 0.0833 | | |
| 3 | 19.3853 | 10958 | 19.3853 | 0.1567 | 0.0271 | 0.0115 |
| 4* | 12.1219 | 13297 | 12.1219 | 0.0733 | | |
| 5 | 17.2198 | 11205 | 17.2198 | 0.1133 | | |
| 6 | 19.1026 | 3743 | 19.1026 | 0.1250 | | |
| 7* | 12.5790 | 14263 | 12.5790 | 0.0933 | | |
| 8* | 13.9738 | 13069 | 13.9738 | 0.1000 | | |
| 9 | 17.9447 | 3920 | 17.9447 | 0.1433 | | |
| 10* | 13.6861 | 11988 | 13.6861 | 0.1000 | | |

Table 14: Twenty Hidden Node Output

| Cycle | Statistic | Epoch | Statistic | Val Set Error Rate | Ave Error Rate or Std Dev | Select Ave Er Rat or St Dev |
|-------------------------|-----------|-------|-----------|--------------------|---------------------------|-----------------------------|
| Training Set | | | | | | |
| 1 | 0.0600 | 3113 | 0.0600 | 0.1533 | 0.1298 | 0.1117 |
| 2* | 0.0400 | 14840 | 0.0400 | 0.1100 | | |
| 3* | 0.0400 | 4677 | 0.0400 | 0.1167 | 0.0233 | 0.0234 |
| 4 | 0.0600 | 3629 | 0.0600 | 0.1417 | | |
| 5 | 0.0500 | 7143 | 0.0500 | 0.1633 | | |
| 6 | 0.0500 | 3610 | 0.0500 | 0.1267 | | |
| 7 | 0.0500 | 6887 | 0.0500 | 0.1267 | | |
| 8* | 0.0300 | 7928 | 0.0300 | 0.1383 | | |
| 9 | 0.0500 | 8589 | 0.0500 | 0.1400 | | |
| 10* | 0.0200 | 9921 | 0.0200 | 0.0817 | | |
| Testing Set | | | | | | |
| 1 | 0.1600 | 1803 | 0.1600 | 0.1600 | 0.1270 | 0.0850 |
| 2* | 0.1100 | 13293 | 0.1100 | 0.0983 | | |
| 3* | 0.1100 | 8932 | 0.1100 | 0.0683 | 0.0350 | 0.0153 |
| 4 | 0.1400 | 2264 | 0.1400 | 0.1433 | | |
| 5 | 0.2000 | 2316 | 0.2000 | 0.1867 | | |
| 6 | 0.1300 | 2077 | 0.1300 | 0.1317 | | |
| 7 | 0.1400 | 10195 | 0.1400 | 0.1183 | | |
| 8 | 0.1500 | 7693 | 0.1500 | 0.1333 | | |
| 9 | 0.1700 | 5058 | 0.1700 | 0.1417 | | |
| 10* | 0.0700 | 2638 | 0.0700 | 0.0883 | | |
| Weighted Average | | | | | | |
| 1 | 0.1300 | 3113 | 0.1300 | 0.1533 | 0.1233 | 0.0906 |
| 2* | 0.0900 | 12944 | 0.0900 | 0.1083 | | |
| 3* | 0.0850 | 8922 | 0.0850 | 0.0817 | 0.0284 | 0.0154 |
| 4 | 0.1250 | 2264 | 0.1250 | 0.1433 | | |
| 5 | 0.1400 | 7143 | 0.1400 | 0.1633 | | |
| 6 | 0.1100 | 2229 | 0.1100 | 0.1250 | | |
| 7 | 0.1050 | 13571 | 0.1050 | 0.1050 | | |
| 8 | 0.1100 | 7928 | 0.1100 | 0.1383 | | |
| 9 | 0.1250 | 7411 | 0.1250 | 0.1333 | | |
| 10* | 0.0600 | 9921 | 0.0600 | 0.0817 | | |

Table 14: Twenty Hidden Node Output (continued)

| Cycle | Statistic | Epoch | Statistic | Val Set Error Rate | Ave Error Rate or Std Dev | Select Ave Er Rat or St Dev |
|-----------------------------|-----------|-------|-----------|--------------------|---------------------------|-----------------------------|
| Moving Average | | | | | | |
| 1 | 0.1680 | 2222 | 0.1680 | 0.1500 | 0.1255 | 0.0872 |
| 2* | 0.1180 | 13297 | 0.1180 | 0.1083 | | |
| 3* | 0.1120 | 8936 | 0.1120 | 0.0733 | 0.0336 | 0.0186 |
| 4 | 0.1560 | 2264 | 0.1560 | 0.1433 | | |
| 5 | 0.2000 | 2370 | 0.2000 | 0.1867 | | |
| 6 | 0.1380 | 2077 | 0.1380 | 0.1317 | | |
| 7 | 0.1420 | 12431 | 0.1420 | 0.1117 | | |
| 8 | 0.1580 | 7693 | 0.1580 | 0.1333 | | |
| 9 | 0.1780 | 5060 | 0.1780 | 0.1367 | | |
| 10* | 0.0840 | 9292 | 0.0840 | 0.0800 | | |
| Total Absolute Error | | | | | | |
| 1 | 19.1617 | 3763 | 19.1617 | 0.1350 | 0.1197 | 0.0833 |
| 2* | 15.5814 | 13294 | 15.5814 | 0.1067 | | |
| 3* | 12.2777 | 8934 | 12.2777 | 0.0700 | 0.0306 | 0.0203 |
| 4 | 17.8040 | 4848 | 17.8040 | 0.1383 | | |
| 5 | 23.5986 | 9261 | 23.5986 | 0.1650 | | |
| 6 | 16.6230 | 2711 | 16.6230 | 0.1183 | | |
| 7 | 15.0833 | 13539 | 15.0833 | 0.1100 | | |
| 8 | 18.5888 | 9806 | 18.5888 | 0.1467 | | |
| 9 | 18.4043 | 6421 | 18.4043 | 0.1333 | | |
| 10* | 11.6428 | 14751 | 11.6428 | 0.0733 | | |

Vita

Captain Bruce Kostal was born on 22 September 1959 in Beatrice, Nebraska. He was graduated from the University of Nebraska in 1982 with a Bachelor of Science degrees in Business Administration (Accounting). After graduation, he was assigned to Whiteman AFB, Missouri as a Missile Launch Officer. There, he also received a Master of Business Administration (Personnel Administration) degree and a Certified Public Accounting Certificate (State of Nebraska). In 1987, he was transferred to Vandenberg AFB, California, as a member of the Top Hand program, which is responsible for operational missile test launches. In August 1992, he entered the Strategic and Tactical Sciences Program, School of Engineering, Air Force Institute of Technology, Wright-Patterson AFB, Ohio.

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Bibliography

1. Belue, Capt Lisa M. *An Investigation of Multilayer Perceptrons for Classification*. MS thesis, AFIT/GOR/ENS/92M-06. School of Engineering, Air Force Institute of Technology(AU), Wright-Patterson AFB OH, March 1992.
2. Choie, YoungJu and others. "On Benchmarks for Learning Algorithms," *1991 IEEE International Joint Conference on Neural Networks*, 1 723-728. New York: IEEE Press, 1989.
3. Guyon, I. "Neural Networks and Applications Tutorial," *Physics Reports*, 207 (3-5): 215-259 (September 1991).
4. Hart, Anna. "Using Neural Networks for Classification Tasks-Some Experiments on Datasets and Practical Advice," *OR: Journal of the Operational Research Society*, 43 (3): 215-226 (March 1992).
5. Choie, YoungJu and others. "On Benchmarks for Learning Algorithms," *1991 IEEE International Joint Conference on Neural Networks*, 1 723-728. New York: IEEE Press, 1989.
6. Hergert, F. and others. "A Comparison of Weight Elimination methods for Reducing Complexity in Neural Networks," *International Joint Conference on Neural Networks*, 3 980-987. New York: IEEE Press, 1992.
7. Müller, B. and J. Reinhardt. *Neural Networks: An Introduction*. Berlin: Springer-Verlag, 1990.
8. Nelson, Marilyn McCord and W. T. Illingworth. *A Practical Guide to Neural Nets*. Reading, MA: Addison-Wesley Publishing Company, Inc., 1991.
9. Pan, H.-L. and Y.-C. Chen. "Liver Tissues Classification by Artificial Neural Networks," *Pattern Recognition Letters*, 13 (5): 355-368 (May 1992).
10. Ramamoorthy, C. V. and S. Shekhar. "A Stochastic Learning Algorithm for Generalization Problems," *TENCON '89 Fourth IEEE Region 10 International Conference. 'Information Technologies for the 90's'* 136-141. New York: IEEE Press, 1989.
11. Rogers, Steven K., Matthew Kabrisky, Dennis W. Ruck, and Gregory L. Tarr. *An Introduction to Biological and Artificial Neural Networks*. Unpublished Report. Air Force Institute of Technology, Wright-Patterson Air Force Base, OH, 1990.
12. Tou, J. T. and R. C. Gonzalez. *Pattern Recognition Principles*. Reading, MA: Addison-Wesley Publishing Company, 1974.
13. Weiss, Sholom M. and Casimir A. Kulikowski. *Computer Systems That Learn: Classification and Prediction Methods from Statistics, Neural Nets, Machine Learning, and Expert Systems*. San Mateo, CA: Morgan Kaufmann Publishers, Inc., 1991.

14. Wiggins, Vince L. and others. *Neural Networks: A Primer*. Contract F41689-88-D-0251. Human Resources Directorate, Manpower and Personnel Research Division, Brooks Air Force Base, TX, May 1991.

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| 13. ABSTRACT (Maximum 200 words) The goal of this study was to decide when to terminate training of an artificial neural network (ANN). In pursuit of this goal, several characteristics of the ANN were monitored throughout ANN training: classification error rate (of the training set, testing set, or a weighted average of the two); moving average classification error rate; measurements of the difference between ANN output and desired output (error sum of squares, total absolute error, or largest absolute error); or ANN weight changes (absolute weight change, squared weight change, or relative weight change). Throughout this research, the learning rate was held constant at 0.35. The momentum was not used because the primary interest of this study was evaluating when to terminate training as opposed to the speed of reaching a decision. The ANN structure was held constant with two input features, two output classes, and one hidden layer. Finally, the practice of training after processing each exemplar was followed. Results indicated three conclusions. First, multiple runs are required for ANN analysis because ANNs are not guaranteed to converge to the same solution. Second, the classification error rate, a moving average of the classification error rate, and the total absolute error (all computed on the testing set) provided a similar final classification. Third, once the stopping criteria functions cease to decrease, select a set of ANN final weights at random. On average, they yielded as low as or lower classification error rate and variance of the classification error rate than other possible choices. | | | |
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